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Late Palaeozoic post-orogenic volcanism in the Sudetes Mts. and the Kupferschiefer-type Cu-Ag ore deposits in the Fore-Sudetic Monocline, SW Poland

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Introduction

(Marek Awdankiewicz & Zbigniew Sawlowicz)

The area of western and central Europe, west and north of the Alps, is largely covered with Mesozoic and Cenozoic sedimentary rocks, reaching the thickness up to several thousands metres in many places. Older rock complexes, including Precambrian and Palaeozoic crystalline and sedimentary rocks, crop out as isolated massifs, including the Massif Central, the Armorican Massif or the Bohemian Massif (Fig. A1). The massifs may be considered as specific windows, which, through the rocks complexes exposed there, provide insights into pre-Mesozoic stages of development of the European lithosphere. The regional European context of the area described can be found in papers of McCann *et al.* (2006) and Kroner *et al.* (2006).

Field trip PL3 leads into the Lower Silesia region and the Sudetes mountains in south-west Poland, near the border with the Czech Republic to the south and Germany to the west, at the north-eastern margin of the Bohemian Massif. In terms of geology, the pre-Mesozoic rock complex of that region is part of the Palaeozoic Variscan Belt of Europe. This belt in Central Europe can be subdivided into two parts, an internal (internides) and an external zone (externides), separated by the Rheic Suture Zone (Kroner *et al.*, 2008). The pre-orogenic (pre-Variscan) evolution of the region is exceptionally complex and much debated (*e.g.* Mazur *et al.*, 2006). However, the trip PL3 is focused on selected, better-constrained aspects of the post-orogenic development.

The trip and the guidebook are arranged in two parts. The aim of part A is the presentation of selected localities of the Permo-Carboniferous volcanic rocks. These rocks are representative of a major episode of late- to post-orogenic volcanism which affected the Variscan orogen and its foreland in the Carboniferous and Permian times (*e.g.* Wilson *et al.*, 2004). Extensive quarrying and good exposure enable discussion of various aspects of both, regional geology, as well as specific problems of physical volcanology, such as the emplacement processes of the volcanic rocks, the distinction between lavas and subvolcanic intrusions in unconsolidated sediments, and the possibilities of recognition and interpretation of ancient, partly eroded and later buried, volcanic centres. In many places the volcanic rocks are also hosts for interesting mineralisation, filling cracks and amygdales (*e.g.* agates). The aim of part B of the field trip is to present various aspects (structural, sedimentological, mineralogical, and economical) of the giant sedimentary-hosted Kupferschiefer-type copper deposits, located in the south-west part of the Fore-Sudetic Monocline, close to the northern boundary of the Fore-Sudetic Block. These two structural units are separated by a system of faults called the Odra fault zone. Visits to the underground mines will allow studying of the typical vertical ore sections through sandstone, shale and dolomite, the oxidized facies (Rote Fäule), enriched in Au and PGE, sandstone ores with their various features, and to discuss the origin of the Kupferschiefer mineralization.

Part A: Late Palaeozoic volcanism in the Sudetes

Marek Awdankiewicz

A1. Geological setting of the Permo-Carboniferous volcanic rocks in Lower Silesia

A1.1 The regional context

The Sudetes Mts. are located at the north-eastern margin of the Bohemian Massif, in Lower Silesia in south-west Poland (Figs. 1 and 2). The Sudetic Marginal Fault separates the uplifted and mountainous Sudetes block to the SW from the downthrown and hilly Fore-Sudetic Block to the NE. The crystalline basement of the region represents an eastern segment of the Variscan Belt of Europe and comprises deformed, and usually metamorphosed, Upper Proterozoic to Lower Carboniferous rock series intruded with Late Palaeozoic granitoids. This basement is partly overlain by Carboniferous to Permian volcano-sedimentary molasse deposits and by Upper Triassic and Upper Cretaceous sedimentary rocks of the epi-Variscan platform cover. Paleogene and Neogene sedimentary rocks cover most of the

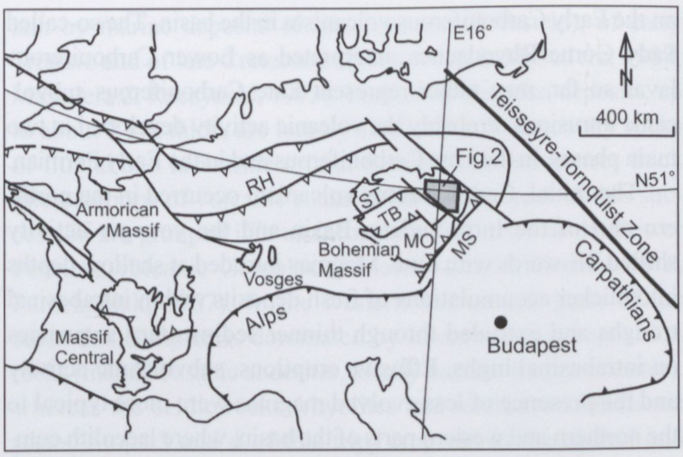

Fig. A1. Location of the Sudetes region (frame) in the Variscan belt of Europe. ST – Saxothuringian, MO – Moldanubian, MS – Moravo-Silesian, RH – Rhenohercynian, TB – Teplá-Barrandian. Modified after Mazur *et al.* (2006).

Fore-Sudetic Block. Cenozoic mafic volcanic rocks (plugs, lava flows, pyroclastic deposits) are locally abundant. Post-glacial Pleistocene deposits are widespread in the Fore-Sudetic Block and less common in the Sudetes.

Similar to other parts of the Variscides, the pre-Permian crystalline rock complexes of the Sudetes provide a record of the late Proterozoic (Cadomian) orogeny followed by Cambro-Ordovician and Devonian rifting and basin opening and, finally, late Devonian to early Carboniferous basin closure, collision and orogeny. The Variscan orogenic processes juxtaposed variably deformed and metamorphosed terranes along major suture zones, and the Sudetic segment of the Variscides was also strongly affected by Late Palaeozoic lateral displacements along NW- and NE-trending regional strike-slip zones (*e.g.* Franke & Żelaźniewicz, 2002; Mazur *et al.*, 2006, and references therein). During the Carboniferous and Permian the Sudetes region

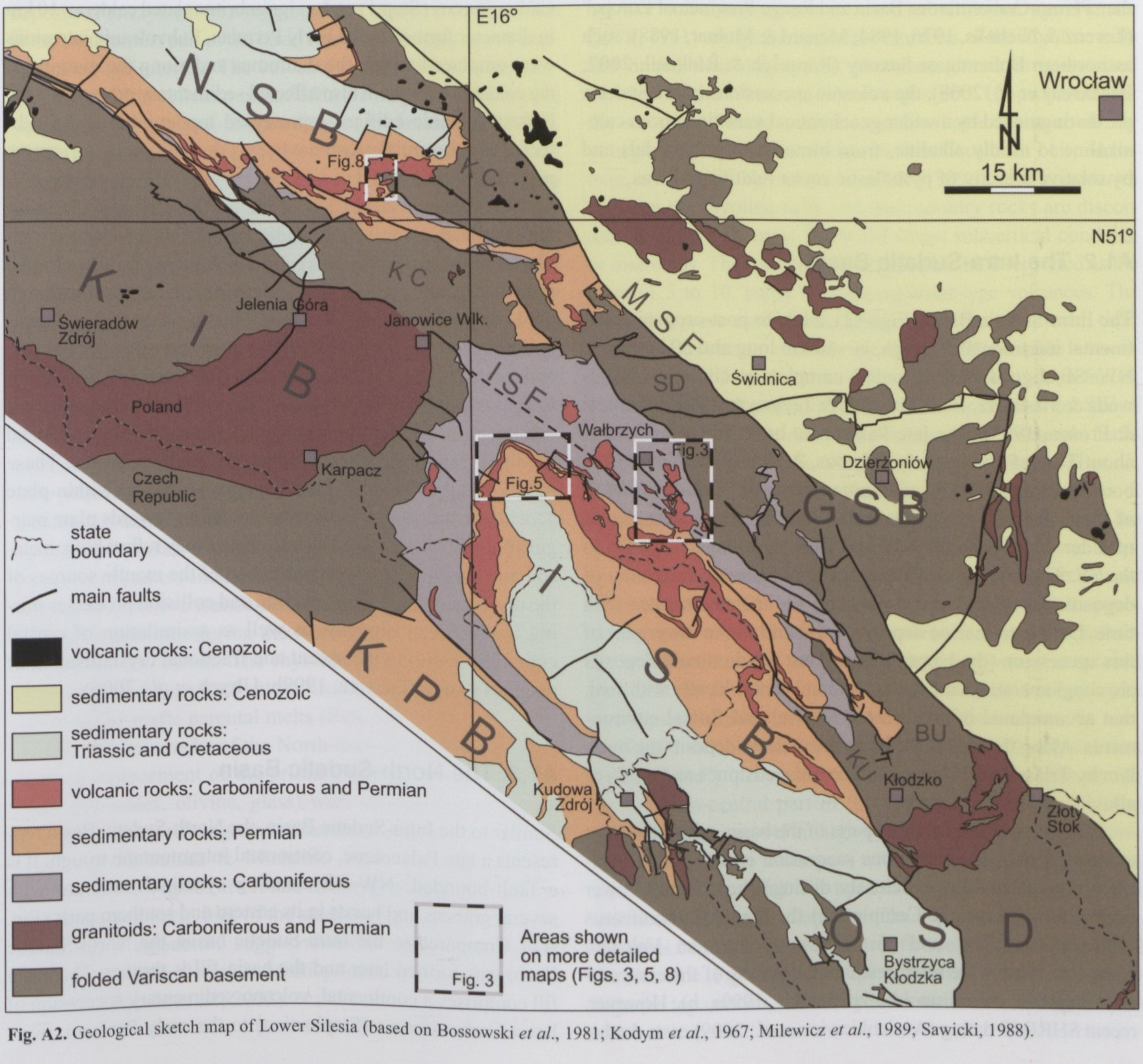

Fig. A2. Geological sketch map of Lower Silesia (based on Bossowski *et al.*, 1981; Kodym *et al.*, 1967; Milewicz *et al.*, 1989; Sawicki, 1988).

was affected by late- to post-orogenic extension and associated formation of intramontane basins, such as the Intra- and North-Sudetic Basins (see below), and intense magmatism.

The origin of this Late Palaeozoic magmatic activity can be generally linked to the detachment of subducted lithospheric slabs, mantle upwelling and melting, crustal melting, and variable interaction of mantle-derived and crustal melts (*cf.* Ziegler & Dezes, 2006). In the Sudetes, the late Palaeozoic igneous rocks fall into two broad categories: 1) plutonic to subvolcanic complexes that comprise granitoid plutons and mafic to felsic dykes cropping out within the uplifted crystalline basement blocks (*e.g.* Awdankiewicz, 2007; Słaby & Martin, 2008, and references therein), and 2) volcanic complexes that are interstratified within the molasse successions of the intramontane basins, including the North-Sudetic Basin, the Intra-Sudetic Basin and the Krkonoše Piedmont Basin (Awdankiewicz, 1999a, b, 2006; Ulrych *et al.*, 2006). Compared to the adjacent areas of the "Permo-Carboniferous Basin and Range Province of Europe" (Lorenz & Nicholls, 1976, 1984; Menard & Molnar, 1988), such as northern Bohemia or Saxony (Rapprich & Řídkošil, 2007; Breitkreuz *et al.*, 2008), the volcanic successions of the Sudetes are distinguished by a wider geochemical variation (from calc-alkaline to mildly alkaline, from bimodal to polymodal) and by relative scarcity of pyroclastic rocks relative to lavas.

A1.2 The Intra-Sudetic Basin

The Intra-Sudetic Basin (Fig. A2), a late to post-orogenic continental intramontane trough, is ~60 km long and 30 km wide, NW–SE aligned, fault-bounded, complex syncline (*e.g.* Wojewoda & Mastalerz, 1989; Dziedzic & Teysseyre, 1990; Mastalerz & Prouza, 1995). The late Palaeozoic basin fill comprises of about 7 km of Lower Carboniferous, 2.5 km of the Upper Carboniferous and 1.5 km of Permian deposits. The distribution of these deposits is asymmetrical, with thicker accumulation of older deposits to the NW and thinner, younger deposits to the SE. These features reflect a general SE-ward migration of depositional centres and decreasing sedimentation rates with time. Deltaic to marine deposits are found in the lower part of this succession (the Upper Viséan), but the dominant deposits are conglomerates, sandstones and mudstones, locally with coal, that accumulated in continental, alluvial and fluvial environments. Along the axis of the basin the molasse deposits are overlain by Triassic and Upper Cretaceous sandstones and marls of alluvial and marine origin.

In the central and northern parts of the basin, where the most complete Permo-Carboniferous succession is found, three volcanic complexes were previously distinguished: 1) the Lower Carboniferous Volcanic Complex, 2) the Upper Carbonifeorus Volcanic Complex, and 3) the Lower Permian Volcanic Complex; these were interpreted as the results of three successive stages of volcanism (Awdankiewicz, 1999a, b). However, recent SHRIMP dating (Awdankiewicz *et al.*, 2009) casts doubts on the Early Carboniferous volcanism in the basin. The so-called Sady Górne Rhyodacites, interpreted as Lower Carboniferous lavas so far, may rather represent Late Carboniferous subvolcanic intrusions. Probably the volcanic activity developed in two main phases, in the Late Carboniferous and in the Early Permian.

The initial, Carboniferous volcanism occurred in the northern part of the Intra-Sudetic Basin and the younger activity shifted SE-wards with time. Magmas intruded at shallow depths into thicker accumulations of fresh deposits within intrabasinal troughs and extruded through thinner sedimentary sequences on intrabasinal highs. Effusive eruptions, subvolcanic activity and the presence of less evolved magmas were more typical to the northern and western parts of the basin, where laccolith complexes and lava-dominated, shield and compound volcanoes developed (*e.g.* Stop 2 of this field trip). The eastern part of the basin was mainly characterized by explosive eruptions of the most evolved rhyolitic magmas: a maar belt formed in the late Carboniferous (Stop 1) and an ignimbrite-related caldera ~10 km in diameter formed in the Early Permian. Subvolcanic intrusions were emplaced within the diatremes and along the margins of the caldera. Volcanism also affected sedimentary processes – the largest volcanic edifices represented topographic highs subjected to substantial erosion whereas the caldera in the eastern part of the basin acted as a lacustrine depositional centre.

The volcanic succession of the northern part of the Intra-Sudetic Basin comprises the older, calc-alkaline sequence (emplaced in the Carboniferous) and the younger, mildly alkaline sequence (emplaced mainly in the Permian, but locally also in the Late Carboniferous). The calc-alkaline sequence is strongly dominated by rhyodacites with minor andesites and basaltic andesites. These rocks show geochemical characteristics similar to convergent plate margin lavas. The mildly alkaline sequence comprises, in order of decreasing abundance, rhyolitic tuffs and rhyolites, trachyandesites and basaltic trachyandesites. These mildly alkaline rocks are largely characterised by within-plate geochemical features, with some gradation towards plate margin affinities. These mixed characteristics may reflect both, metasomatic enrichment or contamination of the mantle sources of the magmas, related to subduction and collision processes during the Variscan orogeny, as well as assimilation of crustal components during the ascent and fractional crystallisation of magmas (Awdankiewicz, 1999b; Ulrych *et al.*, 2006).

A1.3 The North-Sudetic Basin

Similar to the Intra-Sudetic Basin, the North-Sudetic Basin represents a late Palaeoizoc, continental intramontane trough. It is a fault-bounded, NW–SE trending synclinal structure with several grabens and horsts in its eastern and southern parts (Fig. A2). Compared to the Intra-Sudetic basin, the North-Sudetic Basin was formed later and the basin fill is thinner. The basin fill comprises a continental, volcano-sedimentary succession of latest Carboniferous (Stephanian) to the early Permian, overlain by marine deposits of late Permian (Zechstein), of early Triassic and of late Cretaceous (Wojewoda & Mastalerz, 1989; Mastalerz & Raczyński, 1993). The Lower Permian deposits, up to about 2 km thick, are largely siliciclastic sedimentary rocks of fluvial and lacustrine origin. Several hundred metres thick intercalations of volcanic rocks in the middle part of this succession are grouped into an informal unit known as the Lower Permian Volcanic Complex (Milewicz, 1965; Kozłowski & Parachoniak, 1967). In the western and central parts of the basin this complex is dominated by intermediate composition rocks (mainly basaltic andesites, locally basaltic trachyandesites), whereas the acidic rocks (rhyolites and related volcaniclastic rocks; Stops 3 and 4 of this trip) crop out in the central and eastern parts of the basin.

The rhyolites of the North-Sudetic Basin represent mainly lavas and domes (partly subvolcanic), and the associated volcaniclastic rocks comprise pyroclastic as well as epiclastic deposits. Pańczyk (2003) suggested that some of the rhyolites in the easternmost part of the basin represent strongly to extremely welded ignimbrites. The volcanic rocks with an intermediate composition reflect a major effusive stage of the Permian volcanism in the North-Sudetic Basin (Awdankiewicz, 2006). These intermediate lavas possibly erupted from small shield volcanoes and/or fissure vents. However, the location of these volcanic centres is not well constrained. Most lavas are pahoehoe-type flows but subvolcanic intrusions were also emplaced. The activity occurred in several eruptive episodes separated by repose periods. At some localities abundant sedimentary xenoliths, peperites and pillow-like lavas indicate that lava-wet sediment interactions occurred during the emplacement of flows, or during intrusions into unconsolidated sediments.

The intermediate volcanic rocks of the North-Sudetic Basin show a high-K calc-alkaline affinity and trace element characteristics gradational between active continental margin and intra-plate lavas. The magmas probably originated from mantle sources contaminated or metasomatised during the Variscan orogenic processes. Further evolution of the magmas in shallow-level chambers included fractional crystallization, replenishment by primitive mantle-derived magmas and minor assimilation of wall rocks during the latest stages of differentiation (Awdankiewicz, 2006). The rhyolitic melts formed due to a more advanced fractional crystallisation and crustal contamination of the mafic parental melts (Pańczyk, 2003).

The volcanic rocks of the North-Sudetic Basin often show a strong replacement of the primary igneous phases (plagioclase, pyroxenes, olivine, glass) with various post-magmatic minerals (albite, silica-group minerals, carbonates, sheet silicates; *e.g.* Kowalska & Michalik, 1996; Awdankiewicz & August, 1998). Agates are found in amygdales in the intermediate lavas and in cavities of the acidic volcanogenic rocks. K-Ar dating of celadonite suggest that the alteration processes spanned the Late Permian–Middle Jurassic period (252.5 – 177.5 Ma; Pękala *et al.*, 2003).

A2. Field stops

A2.1 Field stop A1: Trachyandesite cryptodome inside a Carboniferous rhyolitic diatreme at Wałbrzych-Podgórze

(N 50°44'26.9", E 16°18'16.5")

The north-eastern part of the Intra-Sudetic Basin is known as the the Wałbrzych Basin. In Carboniferous times, the Wałbrzych Basin was a local, intrabasinal depositional centre. A SSE-trending belt of rhyolitic tuffs, rhyolites and trachyandesites, distinguished as the Eastern Wałbrzych Basin Volcanic Association (Awdankiewicz, 1999a) crops out along the eastern margin of the the Wałbrzych trough (Figs. 2 and 3). Grocholski (1965) considered that the tuffs and associated rocks fill funnel-like volcanic conduits of late Carboniferous age. Nemec (1979, 1981) recognized several lithofacies of the rhyolitic tuffs and linked their origin with phreatomagmatic eruptions and variable modes of transport and deposition. He proposed that the outcrops of these rocks represent a diachronous, southerly younging, maar belt (the Rusinowa-Grzmiąca maar belt). However, as argued by Awdankiewicz (1999a), the boundaries between the rhyolitic tuffs and their country rocks are discordant and the tuffs most likely fill steep, subvertical conduits, or diatremes. These diatremes may further be interpreted as the roots of 5 to 10, partly overlapping maar-type volcanoes. The volcanoes were eroded and, at the present erosion level, their shallow subvolcanic sections are exposed. A possible subaerial equivalent of the diatreme fill, or the volcanic apron facies, are the so called Kamionki Tuffs which crop out 2-3 km SW of the diatreme belt (Fig. A3). The position of the Kamionki Tuffs within the deposits of the Glinik Formation (Bossowski *et al.*, 1994) possibly constrains the age of maar volcanism at Stephanian. As considered by Nemec (*op. cit.*) the activity in the maar belt commenced with explosive, phreatomagmatic eruptions of rhyolitic magmas. This activity created the main volume of volcaniclastic fill of the diatremes, including various pyroclastic and minor intrusive volcaniclastic deposits. Subsequently, rhyolitic and trachyandesitic magmas were emplaced both into the fill of the diatremes and into their country rocks as dykes, sills, plugs, small laccoliths and lava domes.

Stop 1 of this field trip is an abandoned trachyandesite ("melaphyre") quarry located at the margin of a diatreme in the northern-central part of the volcanic belt (Fig. A3). The quarry exposes an ~45 m high section of the diatreme fill: trachyandesites in the lower part, and sedimentary and pyroclastic rocks above (Fig. A4a). The trachyandesite body is oval in shape and about 250 m in diameter. The top contact of trachyandesites is conformable with a stratification of the clastic fill of the diatreme (Fig. A4b) and dips at about 40° to the east. Away from the top contact, the trachyandesites are massive and show

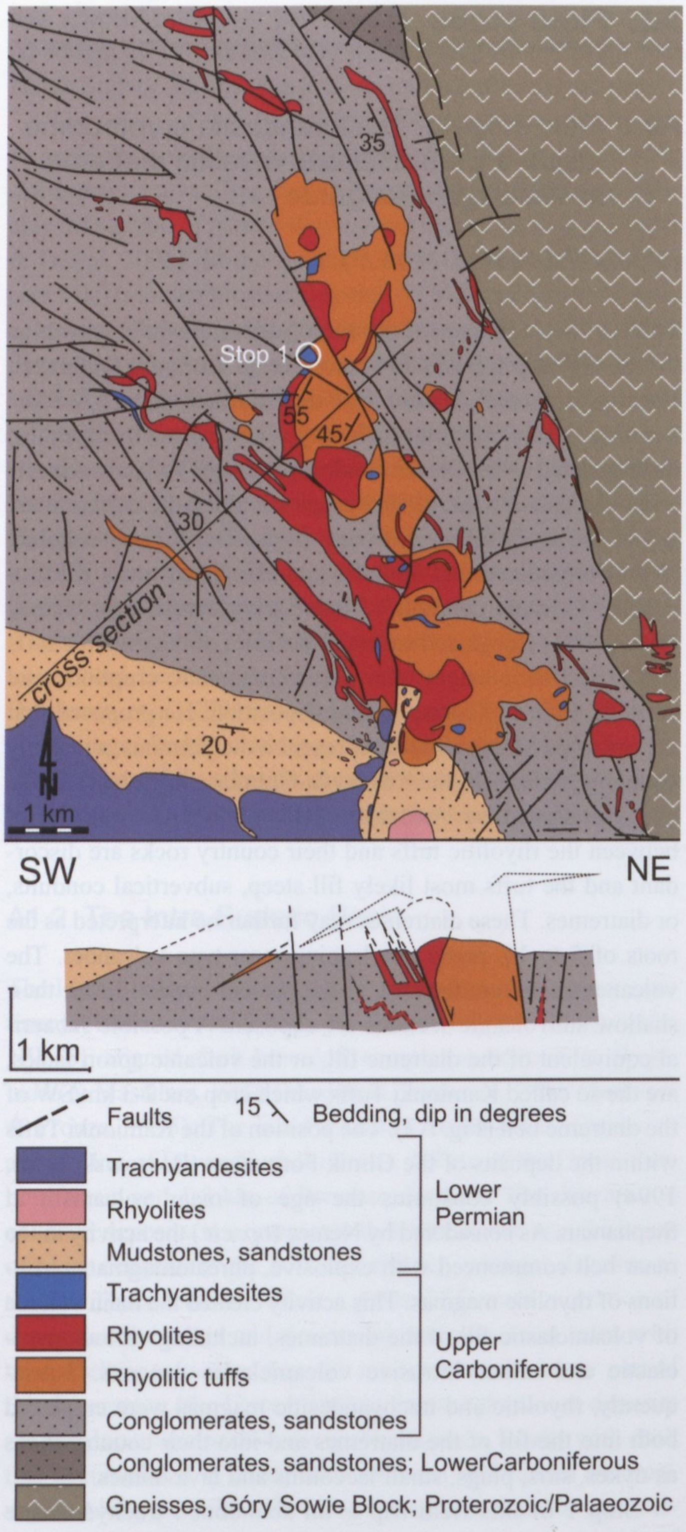

Fig. A3. Geological sketch map and cross-section of the Eastern Wałbrzych Basin Volcanic Association (based on Awdankiewicz, 1999a and 2004). The general location of the area is marked in Fig. A2.

irregular to blocky joints. The upper 5-10 m of the trachyandesite is vesicular to massive and banded, with alternating massive and amygdaloidal lenses and pockets cm to dm thick. In the northern part of the quarry, the topmost meter of trachyandesite comprises platy-jointed, flow-folded and *in-situ* brecciated trachyandesites (Fig. A4c) as well as trachyandesite breccias with a mudstone matrix. A 20 cm long trachyandesite offshoot penetrating into the overlying sediments is also apparent. In the central and southern parts of the quarry the uppermost 5 m of the trachyandesite body consists of subrounded trachyandesite blocks ~1-2 m in size separated by thin, curved clastic dykes. Some clastic dykes attain a thickness of up to 2–4 m and penetrate 20–30 m down into the trachyandesite.

Above the trachyandesites there is a 5–15 m thick layer of red and greenish to grey mudstones, sandstones and conglomerates. The thickness of this rock unit increases southwards. In the lower part this sedimentary sequence is locally well bedded (Fig. A4b), but upwards and southwards bedding is usually disrupted and the overall structure is chaotic, characterized by the presence of mixed, lithologically distinct domains, irregular to lensoidal in shape and cm to m in size. Some domains preserve variably oriented bedding. Indistinct clastic dykes and zones of silification can be observed.

The uppermost part of the described section comprises an ~8 m thick bed of rhyolitic tuffs. The basal contact of the tuffs with the sedimentary rocks is uneven, wavy, with metre-sized irregularities (Fig. A4a). The lowermost part of the tuffs may locally show some layering, but the main part is massive and poorly sorted with angular rhyolite blocks as well as quartz and lithic pebbles in a finer grained matrix of ash. In the north-easternmost part of the quarry the massive tuffs are intercalated by ~1 m thick layers of accretionary lapilli-bearing, laminated tuffs, but the exposure is poor. Southwards the tuff bed may be disrupted into blocks set in sedimentary matrix. In addition, poorly exposed, meter-sized masses of trachyandesite within the rhyolitic tuffs above the quarry may represent discordant apophyses of the main trachyandesite body.

The described section reflects three main, successive events during the development of the diatreme, specifically: 1) an episode of clastic sedimentation, 2) the deposition of rhyolitic tuffs, and 3) intrusive emplacement of trachyandesites into the sequence of sediments and tuffs. These events possibly occurred near the rim of a maar crater, or within the uppermost part of a diatreme.

The sedimentary rocks found between the trachyandesites and the rhyolitic tuffs may represent some alluvial deposits, possibly washed into the maar crater from the surrounding area. However, they are distinct from the grey-coloured and quartz-rich Żacler Formation deposits forming the country rocks of the diatreme nearby. These problematic deposits can be tentatively correlated with the Glinik Formation, which overlies the Żacler Formation. This would imply several hundred m of subsidence of the diatreme fill (Awdankiewicz, 1999a, 2004).

Following Nemec (1981) the massive rhyolitic tuffs in the upper part of the section are interpreted as pyroclastic flow deposits related to phreatomagmatic eruptions. Deposition by a pyroclastic flow is indicated by the massive structure and poor sorting of the deposit, and a phreatomagmatic origin is indicated by abundant xenoliths (pebbles) probably derived

Fig. A4. Structures and textures of volcanogenic rocks at Field stop A1. A – general view of the quarry. The section exposed is ~45 m high and comprises trachyandesites (ta), sedimentary rocks (s) and rhyolitic tuffs (rt). Dotted lines show the boundaries between these main lithologies. Arrows indicate the location of the largest, subvertical clastic dykes within trachyandesites. "B" and "C" show the location of details illustrated in photos B and C, respectively. B – close-up of the contact between trachyandesites (ta) and overlying sedimentary rocks (s). The top of trachyandesites is conformable with the bedding in the overlying mudstones and sandstones and dips to the east. C – close-up of the boundary zone between sedimentary rocks (s) and rhyolitic tuffs (rt). The contact between these rock units is uneven but sharp. The sedimentary rocks comprise mixed domains of various lithology (mudstones, sandstones, conglomerates) and of massive to bedded texture. The rhyolitic tuffs are massive. Hammer for scale is encircled.

from the focus of the eruption, where the rhyolitic magma interacted with wet sediments. However, the poorly exposed, bedded tuff intercalations with accretionary lapilli were rather deposited by pyroclastic surges. These episodes of explosive activity and deposition by pyroclastic density currents can be linked to the main stages in the development of the maar belt.

The trachyandesites are interpreted as a dome-like subvolcanic intrusion into the pyroclastic-sedimentary diatreme fill at a shallow level. At the time of emplacement the country rocks – the sediments and the tuffs – must have been unconsolidated and wet. The interaction of trachyandesite magma with these deposits caused a disruption of bedding in the sedimentary rocks. The sediment/tuff interface has been partly deformed, possibly due to an upward penetration of fluidized masses of sediments and contemporaneous loading of more massive tuffs into the fluidized sediments. The fluidized sediments intruded also downwards into the cooling and fracturing trachyandesite, forming a network of clastic veins near the contact as well as larger dykes penetrating deeper into the trachyandesite. In addition, the trachyandesite magma could have locally pierced the overlying deposits in the form of short dykes or apophyses. The trachyandesite at the contact with wet sediments was locally brecciated due to quenching, forming the *in-situ* breccias. The quenched fragments mixed in places with the fluidized sediments forming the trachyandesite-mudstone (peperitic) breccias.

The general form the trachyandesite intrusion is conformable and can be described as a small laccolith. However, the emplacement level of the laccolith could have been very shallow, Thus, the intrusion could have had a topographic expression forming a cryptovolcanic lava dome near the rim of the maar (*cf.* Cas & Wright, 1987). It can be speculated, that the lateral variation of textures along the contact zone of the trachyandesite (*e.g.* the stronger disruption of the host sequence, and the largest clastic dykes in trachyandesites in the southern part of the quarry) may reflect a partial collapse of the cryptodome to the south-east, towards the centre of the maar crater.

A2.2 Field stop A2: Basaltic trachyandesite lavas, breccias and tuffs and post-magmatic mineralisation – a succession of Permian shield volcano at Czadrówek near Kamienna Góra

(N 50°46'16.1", E 16°02'52.1")

The Kamienna Góra Basaltic Trachyandesites crop out in the north-western part of the Intra-Sudetic Basin (Figs. 2 and 5) as the lowermost member of the Lower Permian Volcanic Complex (Awdankiewicz 1999a, b). These mafic rocks with silica content of 52% represent the earliest and silica-poorest volcanic products of the Permian volcanic stage in the Intra-Sudetic Basin.

The outcrop of the Kamienna Góra Basaltic Trachyandesites represents a small, buried shield volcano, about 10–12 km in diameter, 0.1 km high, and 1–4 km^3 in volume (Awdankiewicz, 1997, 1999a; Awdankiewicz *et al.*, 2003). The volcanic sequence comprises various types of lava flows: aa, pahoehoe and block lavas (Fig. A5). Abundant sedimentary xenoliths, various lava-sediment breccias, peperites and clastic dykes reflect lava-wet sediment interactions during the emplacement of many lava flows. Thin tuff intercalations were locally deposited by pyroclastic surges related to episodic phreatomagmatic eruptions. The correlation of well exposed sections (Fig. A5, sections 1 to 5) points to a westward younging of the lava flow succession, due to a specific palaeogeographic control (Fig. A6). The volcano formed at an alluvial plain, over an easterly inclined palaeoslope. The oldest lavas flowed to the east and partly levelled out the weak topographic gradient. Consequently, the younger flows were successively shifted northwards, westwards and then south-westwards, eventually completing the whole shield in an anticlockwise fashion.

Stop 2 at Czadrówek is 1–2 km west/north-west of the inferred vent of the volcano. The sequence exposed there is about 35 m thick, dips gently to the SE and consists of three successive lava horizons, marked B, C and A in section 4, Fig. A5. Sandstones and tuffs are interbedded between the two lower flows. Sedimentary rocks are also found in breccias and as clastic dykes and xenoliths in the upper part of the section.

The lowermost part of the section (Fig. 7a) comprises an ~8-10 m thick aa lava flow. Its brecciated and rough top is covered by 20 to 40 cm of red-brown, poorly consolidated vol-

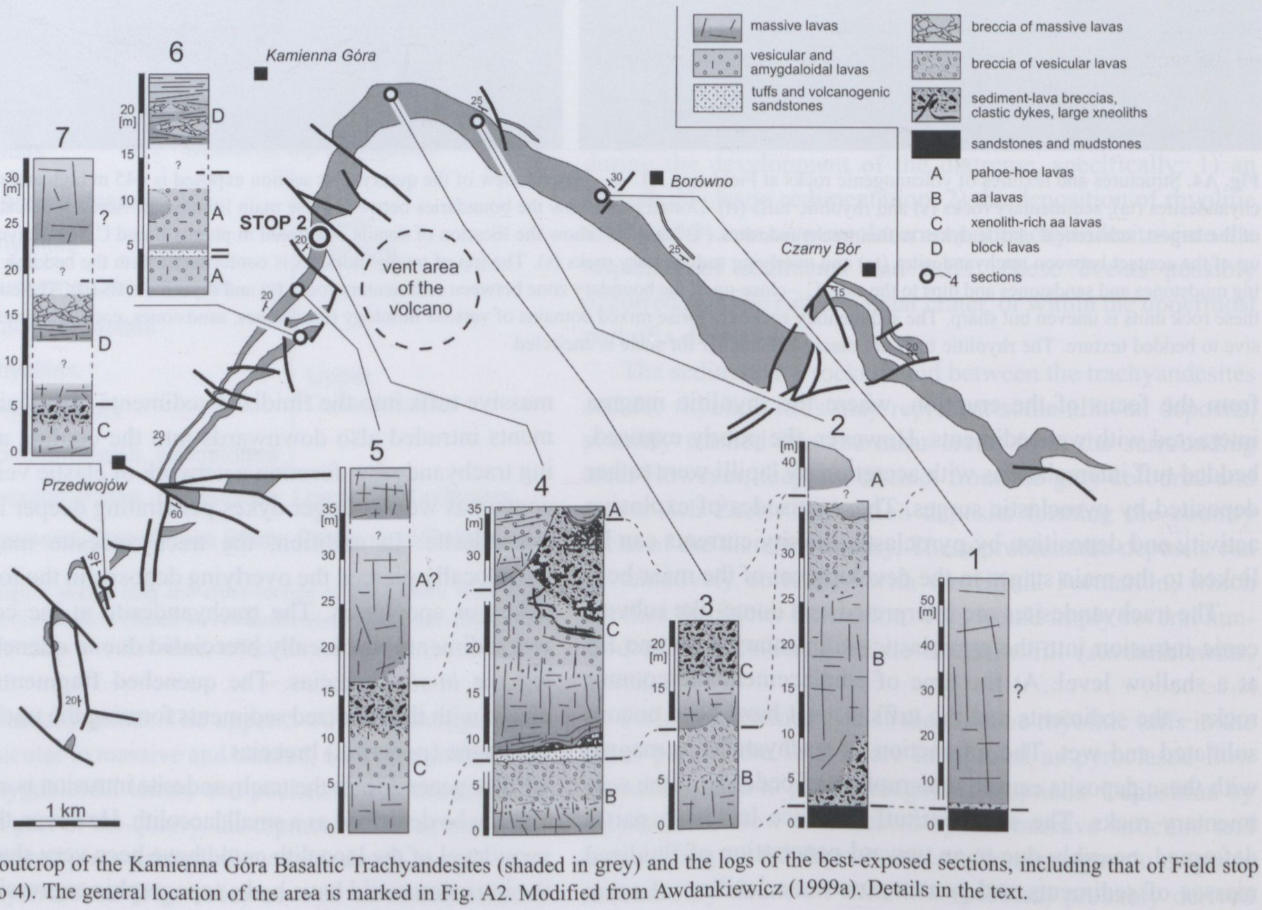

Fig. A5. The outcrop of the Kamienna Góra Basaltic Trachyandesites (shaded in grey) and the logs of the best-exposed sections, including that of Field stop A2 (section no 4). The general location of the area is marked in Fig. A2. Modified from Awdankiewicz (1999a). Details in the text.

canogenic sandstones composed of local lava fragments. These volcanogenic sandstones are discontinuously overlain by thin layer (1–2 cm) of green sandstones of non-volcanic provenance (sublithic arenites). Above, there is an ~1 m thick bed of laminated tuffs which show subhorizontal to indistinct low-angle cross lamination. The tuffs are overlain by an ~25 m thick aa-type lava flow with a massive to vesicular interior and marginal zones composed of variable lava-sediment breccias (Fig. A7b). The breccias, up to 10 m thickness, consist of sandstone and mudstone blocks in a lava matrix (Fig. A7c), but breccias of lava blocks in a sedimentary matrix are also found. Clastic dykes cutting the lavas are common, and locally sedimentary rafts up to 8 m long and 0.3 m thick, partly deformed, occur as well. The massive central part of the flow is characterized by irregular to blocky joints. Locally there are domains 5–10 m in size, characterized by distinct, more regular joints. For example, in Fig. A7b a distinctive structural domain within the flow is defined by concentric and radial joints. The outer limits of this domain are irregular, defined by interfingering of massive lavas with lava-sediment breccias. The top of the described flow is also irregular and shows meter-sized ridges and depressions, the latter filled by massive to vesicular lavas (marked "A" in section 4, Fig. A5).

The described sequence reflects two eruptions of the Kamienna Góra shield volcano. The eruptions were separated by a longer repose period. The second eruption comprised three phases with variable character.

The first eruption was effusive and resulted in the emplacement of an ~10 m thick aa lava flow forming the lowermost part of the section. The red-brown, poorly consolidated volcanogenic sandstones found above are interpreted as a local deposit, formed due to weathering and epiclastic reworking of the top of the underlying aa flow. However, the green sublithic arenites found above document a supply of non-volcanogenic clastic material, probably by alluvial (or aeolian?) processes. A relatively long period of time seems necessary for the accumulation of these deposits and this can be associated with a repose period of the volcano.

The sequence above reflects another major eruption with three phases following rapidly each other. The laminated tuffs accumulated during the initial explosive phase. The fine-grained texture and the style of lamination of this deposit suggest deposition by a pyroclastic surge related to a phreatomagmatic eruption. The overlying 25 m thick lava flow formed during the main, effusive stage of the eruption. Abundant sedimentary xenoliths, lava-sediment breccias (peperites) and clastic dykes point to lava-wet sediment interactions during the emplacement of this flow. The sedimentary material could have been incorporated into the lava flow when in emerged from the vent onto the surface and/or during the flowage over fresh sediments of an intrabasinal alluvial plain. It is noteworthy that the association of epiclastic deposits over the lowermost flow with the initial phreatomagmatic surge deposits above and with the abundant sedimentary component in the main aa flow is consistent with a longer repose period of the Kamienna

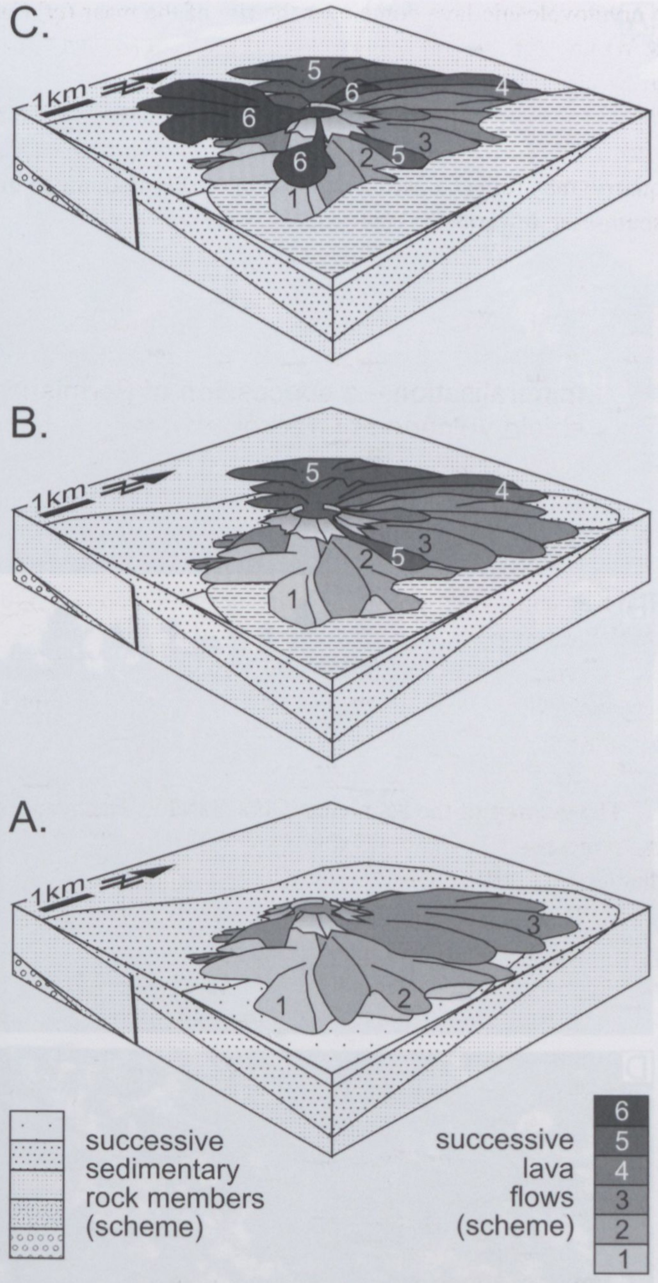

Fig. A6. Palaeogeographic reconstruction of the Kamienna Góra basaltic trachyandesite shield volcano, showing successive stages of development (A to C). Modified from Awdankiewicz *et al.* (2003).

Góra volcano. During this period the vent area could have been partly covered by epiclastic sediments, and the new eruption must have pierced the cover, giving way to the various interactions with wet sediments. In addition, the distinct structural domains within the main flow, defined by specific jointing patterns, are interpreted as lava-filled tubes. The NW–SE to W–E alignment of these tubes, inferred from sections along the quarry walls, suggest the location of the vent of the volcano to be to the E–SE of Stop 2. Finally, the terminal phase of the eruption comprised effusion of pahoe-hoe lava flows. These flows did not carry sedimentary xenoliths – the vent was probably cleared-up during the preceding eruptive phase. These pahoe-hoe flows were of relatively small volume and accumu-

Fig. A7. Examples of structures and texture of the Kamienna Góra Basaltic Trachyandesites at Field stop 2. A – the lower part of the volcanic sequence, showing brecciated top of aa lava blow (br) overlain by volcanogenic sandstones (s) and basaltic trachyandesite tuffs (t). Above there are basaltic trachyandesite breccias (br) and massive lavas (ml) forming the basal part of aa lava flow. 1-m high stick (for scale) can bee seen to the left of the photo centre. B – the middle and upper part of the section. The quarry wall is ~20 m high. This part exposes mainly massive lavas (ml) and lava-sediment breccias (br), forming a xenolith-rich aa flow. A lava-filled tube defined by concentric and radial joints (dotted lines) can be seen. Along the top there is a discontinuous cover of pahoe-hoe lava flows composed of massive to vesicular lavas (ml and vl, respectively; base marked by the broken line). Fore more detailed description and interpretation see the text. C – an example of lava sediment breccia, with sandstone blocks (s) enclosed in matrix of amygdaloidal lava (al). Lens cup, 52 mm in diameter, for scale. D – photomicrograph (crossed polars) of the groundmass of the basaltic trachyndesite. The main minerals in this rock are aligned plagioclase laths (pl), subhedral to anhedral augite (aug), interstitial smectite (sm) and Fe-Ti oxides (black, not well seen). E – scanned thin section of amygdaloidal basaltic trachyandesite. The rock comprises small phenocrysts of altered plagioclase set in a microcrystalline groundmass. The amygdales are filled with chlorites and carbonates.

lated in depressions over the top of the underling aa flow as several lobes forming a discontinuous cover.

The Kamienna Góra basaltic trachyndesites are sparsely porphyrytic to microcrystalline rocks which contain phenocrysts of plagioclase and altered olivine in a groundmass of plagioclase (partly overgrown by alkali feldspar), clinopyroxene, Fe-Ti oxides and altered interstitial glass (Awdankiewicz, 1997, 1999b). Plagioclase ranges from An_{65} to An_{30}, shows normal to oscillatory zoning. The phenocrysts are more calcic than groundmass laths. Alkali feldspars are sodic sanidine to anorthoclase (Or_{60} to Or_{20}), clinopyroxene is augite in composition and the Fe-Ti oxides represent ilmenite and Ti-magnetite. The secondary minerals that replace olivine and glass even in the relatively fresh samples are mainly sheet silicates (chlorite, smectites, celadonite). However, lavas of the outer, vesicular to amygdaloidal sections of the flows are strongly altered. Plagioclase is albitized and the ferromagnesian minerals and the groundmass glass are replaced by variable combinations of sheet silicates (the same minerals as above), carbonates (calcite, more rarely dolomite and other carbonates) and microcrystalline quartz. Amygdales are filled by chlorites, carbonates and quartz, the last found as agate or, more rarely, small geodes of smoky quartz or amethyst. This secondary mineralization developed due to post-magmatic and/or diagenetic processes.

A2.3 Field stop A3: Organy Wielisławskie – columnar jointed and flow-foliated Permian lavas near Sędziszowa

(N 51°02'05.8", E 15°52'07.4")

Stop 3 is an old quarry of Permian rhyolites located in the North-Sudetic Basin, north of the village of Sędziszowa (Figs. 1 and 8), on the western slope of Wielisławka Hill (Fig. A9a). The locality is known as Organy Wielisławskie (Wielisławka Organ) due to well developed columnar joints in the rhyolites, resembling organ pipes. The quarry is protected as a nature monument.

The area visited (Fig. A8) exhibits crystalline basement rocks overlain by Late Carboniferous and Permian volcanic and sedimentary rocks of the North-Sudetic Basin (Fig. A8). The outcrop of the basement rocks (here represented by Lower Palaeozoic, low-grade, mainly metasedimentary rocks of the Kaczawa Complex) is partly fault-bounded and it is known as the Świerzawa horst. The Wielisławka Rhyolites form a NEE-aligned outcrop ~0.4×1.2 km in size, which is mainly set within the basement rocks near the western edge of the horst. However, to the west the rhyolites interfinger with the Late Palaeozoic fill of the North-Sudetic Basin. In addition, several smaller outcrops of rhyolites and rhyolite tuffs straddle the margin of the Świerzawa horst further south. Details are obscured by extensive Quaternary cover.

The Organy Wielisławskie quarry exposes an ~35 m high section of flow-banded and columnar-jointed rhyolites (Figs. 9a and b). Flow foliation defines a concentric structure about

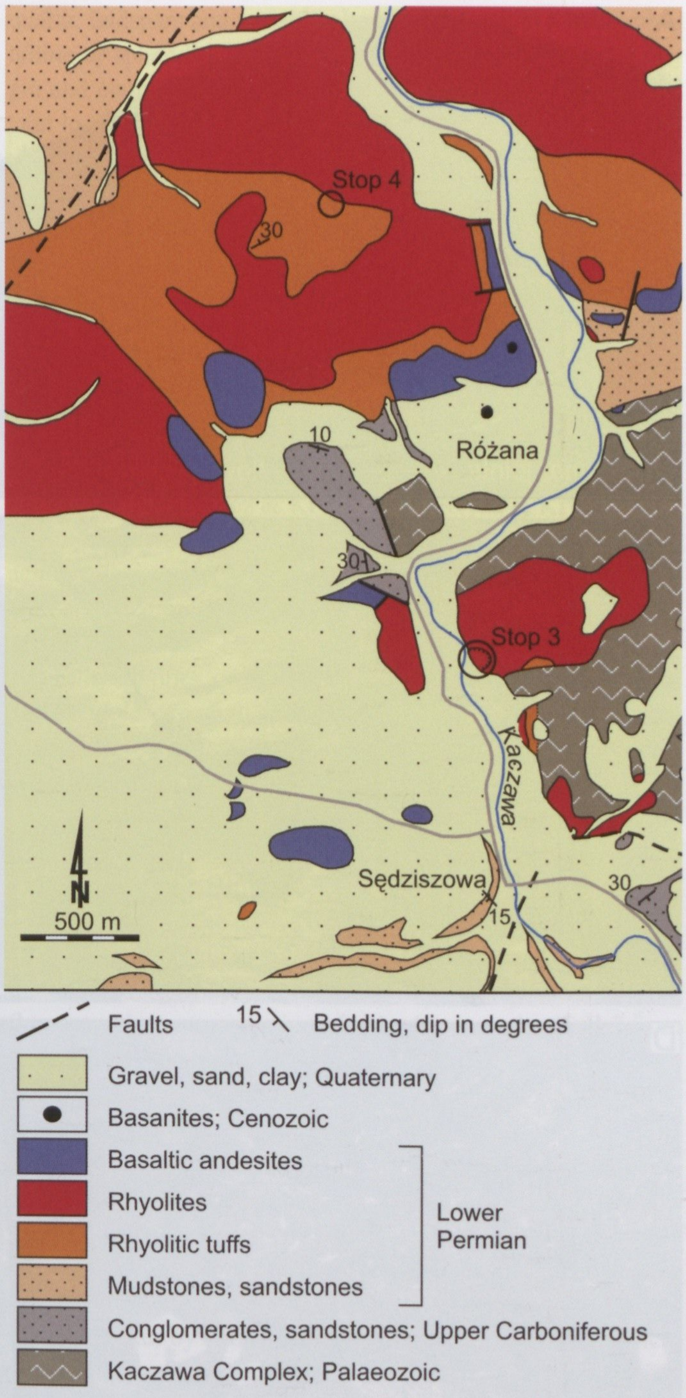

Fig. A8. Geological sketch map of the area near Sędziszowa and Różana in the North-Sudetic Basin. Modified from Frąckiewicz (1958) and Milewicz & Kozdrój (1995).

100 m in diameter with the axis dipping gently (0–35°) to the NE–E. Small flow folds and lineation (Fig. A9c) show a similar but locally variable alignment. The columnar joints are perpendicular or slightly oblique relative to the flow foliation planes and form a fan-like pattern converging towards the axis of the exposed structure: southerly dipping, gently to moderately inclined columns (30–65°) occur in the SE part of the quarry (Fig. A9b), but northwards the columns gradually become more steep to subvertical. The inner part of the exposed struc-

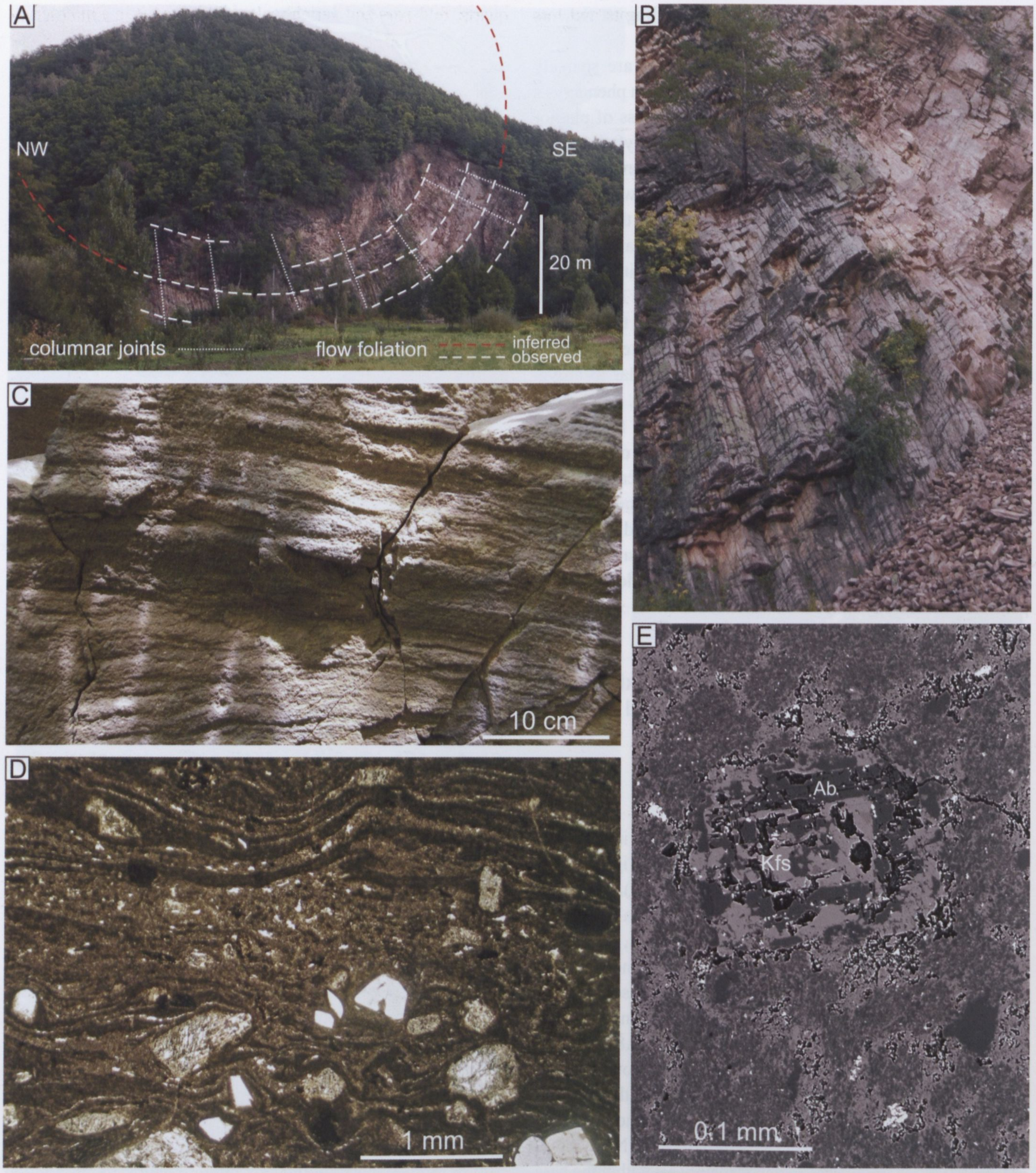

Fig. A9. Rhyolites exposed at the Organy Wielisławskie locality (Field stop 3). A – general view of the Wielisławka Hill and the quarry. The concentric arrangement of flow foliation planes (broken lines) and the radial arrangement of columnar joints (dotted lines) define an oval structure ~100 m wide. B – close-up of the SE part of the quarry showing the columnar joints (dipping to the right in this photo) and the flow foliation (dipping to the left). The fragments of broken polygonal columns forming the talus are usually 15-20 cm in diameter. C – flow-foliation plane with subhorizontal to gently inclined lineation defined by small-scale fold axes. D – plane-polarized photomicrograph of a typical rhyolite from the locality, showing fine-scale lamination and phenocrysts of quartz and feldspars. E – back-scattered electron image of the rhyolite. A feldspar phenocryst composed of intergrown K-feldspar (Kfs) and albite (Ab) is enclosed in a groundmass with abundant recrystallized spherulites (?). The latter are ~0.05-0.1 mm in diameter and consist of finely intergrown alkali feldspars surrounded by a rim enriched in K-feldspar.

ture is more chaotic, with blocky to irregular joints and less clear relationships between flow foliation and joints.

The rhyolites from the quarry typically (Fig. A9d) contain up to about 35% phenocrysts (< 4 mm in size) of quartz, Na-K feldspar (Or_{72} to Or_{99}, also intergrowths of albite), albite pseudomorphs after plagioclase, and biotite (Mg/Mg+Fe ? 0.4) strongly replaced by chlorite (close to diabantite in composition). Quartz phenocrysts are rounded and embayed, with small apatite inclusions. The very finely laminated, felsitic and haematite-rich groundmass is mainly composed of anhedral quartz and alkali feldspars. Two types of laminae are distinguished: the predominant set is lighter and contains aligned quartz streaks, the subordinate set is haematite-rich without distinctive quartz. Indistinct spheroidal textures are developed locally (Fig. A9e). Nearly aphanitic rhyolites with subvertical columnar joints occur locally above the quarry and near the top of Wielisławka Hill.

The rhyolites exposed at Organy Wielisławskie may represent a gently inclined plug or, more likely, an inner part (a root?) of lava dome. The groundmass textures of the rhyolites suggest relatively slow cooling and crystallization of the rhyolite magma, consistent with this interpretation. Flow banding and variable phenocryst contents may indicate extrusion and mingling of compositionally heterogeneous magma batches. The original mineralogy and textures are partly overprinted by post-magmatic alteration. However, the structure exposed at the Sędziszowa quarry is only a small part of the larger, still poorly described outcrop which requires further detailed study (Awdankiewicz & Szczepara, 2009).

A2.4 Field stop A4: Agates in Permian, acidic volcanogenic rocks at "Piekiełko", south of Nowy Kościół

(N 51°03'05.6", E 15°51'40.4")

Stop 4 is a steep-sided, forested valley between the villages of Nowy Kościół and Różana in the SE part of the North-Sudetic Basin (Figs. 1 and 8). This valley, known as Piekiełko ("Little Hell") is one of the most famous sites of agate occurrence in Lower Silesia (*e.g.* Kryza & Kryza, 1982; Bogdański, 2001).

The chalcedony mineralization in the Nowy Kościół area was first recognized in the XIXth century (Niśkiewicz & Kryza, 1973). This mineralization is found in Permian acidic volcanogenic rocks which are ~150 m thick and comprise volcaniclastic deposits (*e.g.* tuffs, ignimbrites, conglomerates and other rocks, generally mapped as "tuffs") overlain by rhyolites (Kryza & Kryza, 1982). The volcaniclastic rocks contain broken phenocrysts of quartz, plagioclase and biotite as well as volcanic and non-volcanic rock fragments and abundant "devitrified glass dust" (Kozłowski & Parachoniak 1967; Kryza & Kryza, 1982). The rhyolites are porphyrytic and contain phenocryst of quartz, feldspars and variably altered biotite set in a microcrystalline or spherulitic groundmass. However, details on the origin and evolution of the acidic volcanogenic complex, such as vent location(s) or eruptive processes, are not well constrained.

Two forms of chalcedony mineralization have been recognized (Kryza & Kryza, 1982; Kozłowski, 1987): chalcedony veins and agate-bearing nodules. Chalcedony veins are found in the coherent rhyolites and are relatively rare. Agate-bearing nodules occur at several locations near the top of "tuffs" and near the base of rhyolites. The distribution of the agate nodules and textural features such as star-shaped agate forms and spherulitic textures in their host rocks indicate that the agates formed in (originally) glassy parts of silicic lava flows and/or in densely welded ignimbrites, and that some of them represent lithophysae (*cf.* Niśkiewicz & Kryza, 1973; Kryza & Kryza 1982).

The agate-bearing nodules are especially abundant in the acidic volcanogenic rocks at "Piekiełko". The nodules occur in a soft, clay-rich rock which fills irregular cavities in more coherent rhyolitic rocks. The clay-rich rock is composed of illite, Fe and Al hydroxides, quartz and alkali feldspar (Kryza, 1983). The agate nodules are up to several tens of cm in size and the largest specimens found in this vicinity were up to 100 kg in weight, but strongly cracked (Bogdański, 2001). Most commonly the agates show a concentric type of banding, but other types are also found (Fig. A10). Some agates contain a central cavity with crystals of quartz or its coloured varieties (*e.g.* amethyst).

The origin of the agates of the Nowy Kościół area has been linked to weathering of spheroidal-textured "porphyries", accumulation of "porphyry balls" over the weathered top or lava flows, and later precipitation of silica between the "balls" from descending waters (Müller, 1896, vide Niśkiewicz & Kryza, 1973). Niśkiewicz & Kryza (1973) and Kryza & Kryza (1982) suggested that the agates formed mainly as a result of the decomposition of glass-rich volcanogenic rocks by post-volcanic fluids and solutions, with less important influence of weathering processes. Kryza (1983) noted the association of agate nodules with characteristic clay-rich rocks and considered that this association formed due to the decomposition of primary rhyolites by hydrothermal solutions. Mass-balance calculations suggest that the decomposition of rhyolite occurred in a partly open system, or that it may be that the primary rhyolite composition was different from that used in calculation.

A2.5 Acknowledgements

Christoph Breitkreuz and Andrzej Muszyński are acknowledged for helpful discussions and suggestions on the characteristics and interpretations of the sections of volcanic rocks presented in this contribution. Thanks are due to Jacek Bogdański who provided slides of agates from his collection. Volker Hoeck is thanked for a review.

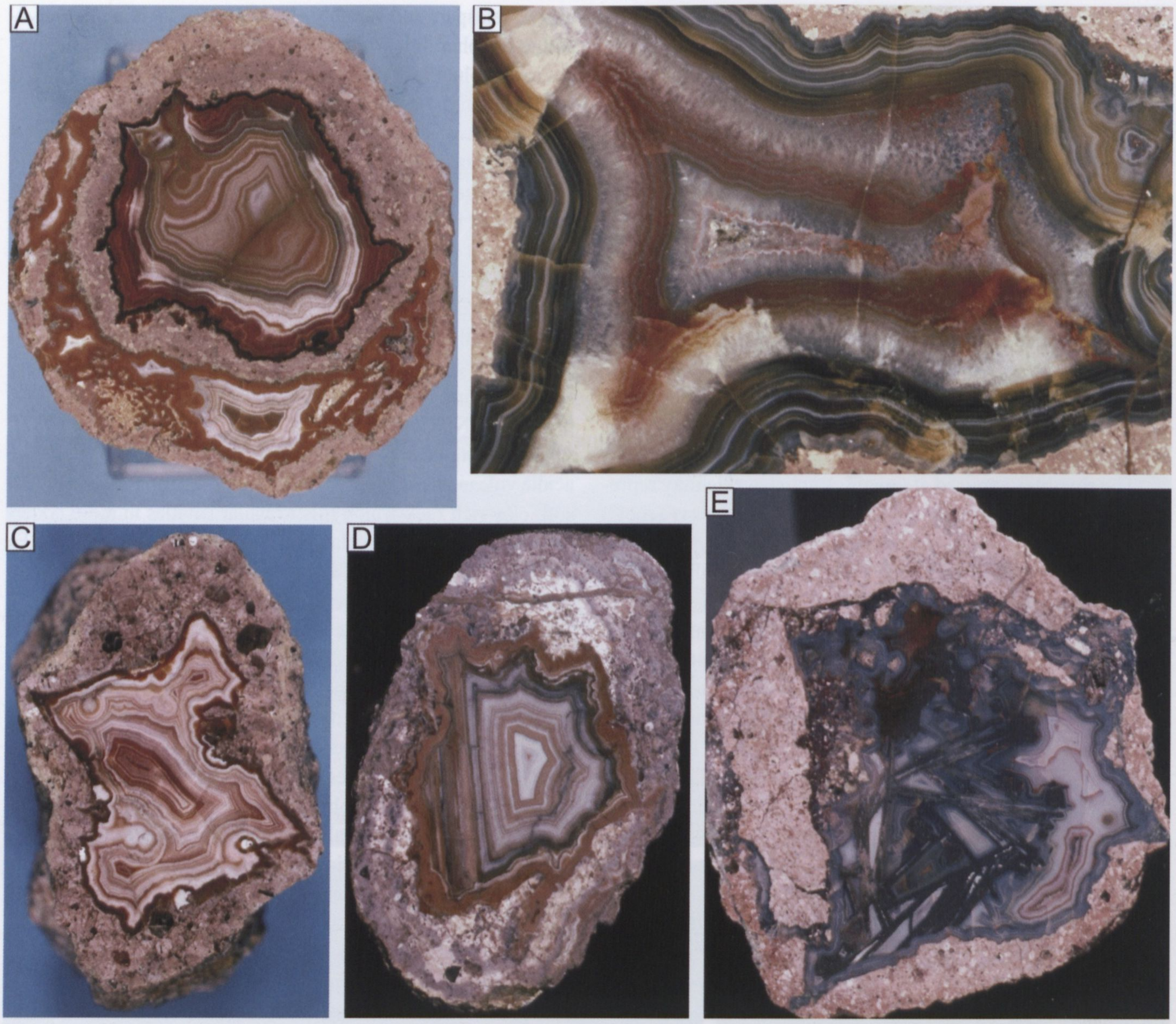

Fig. A10. Examples of agates from the vicinity of Field stop 4. All specimens from the collection of J. Bogdański, photographs by F. Kauffungen. A – a typical, concentrically banded agate in a "porphyry" nodule. Diameter 12 cm. B – close-up of agate showing finely laminated and more coarsely banded zones. Field of view ~7 cm wide. C – agate with more irregular outline and a polycentric texture. Diameter ~8 cm. D – stratified to concentrically banded, Uruguay-type agate. Diameter ~7 cm. E – polygonal, Paraíba-type agate. Diameter 10 cm.

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Part B. Sediment-hosted copper-silver deposits in the Lubin-Glogow mining district (Poland)

Jadwiga Pieczonka, Adam Piestrzyński and Zbigniew Sawlowicz

B1. Introduction

The first clear signs of the rich copper ores in this area were found in 1957, in the borehole Sieroszowice IG-1, at depths of 601.20–603.5 m. However, the presence of metal-bearing black shale ("Kupferschiefer") in the Fore-Sudetic Monocline had been recognized a few years earlier. Prospecting and documenting the copper ore reserves were supervised by Jan Wyżykowski from the Polish Geological Institute. The first documentation, based on 24 boreholes was completed in 1959. Over a surface of 175 km², 1,364,652,000 tons of ore was proven, containing 19,339,000 tons of metallic copper. On 20th March, 1963, the first copper ore was extracted from the "Boleslaw" shaft of the Lubin Mine in the eastern part of the copper district. Now, there are 10 fields operating in three mines – Lubin, Rudna, and Sieroszowice-Polkowice, all belonging to the huge company KGHM Polska Miedź S.A. Each mine has its own flotation plant.

Economic ore reserves are in the depth interval of 850–1270 m in the Rudna Mine, 400–1350 m in the Sieroszowice-Polkowice Mine, and 370-910 m in the Lubin Mine. The KGHM Polska Miedź S.A. owns the following licenses: Małomice – 75.5 km², Lubin – 82.70 km², Polkowice – 75.65 km², Rudna 75.6 km², Sieroszowice 96.99 km², and two reserve areas: Radwanice 61.4 km², and Gaworzyce 48.2 km² (Fig. B1). This amounts to 406.44 km² of mining area, and 109.6 km² of reserve area. To the north there is still a potential area up to a depth of 1,600 m. Glogow Gleboki is a new field under preparation for mining activity. For organizational reasons, the ore is exploited by three mines but they all are connected underground and form one of the biggest underground mine systems in the world.

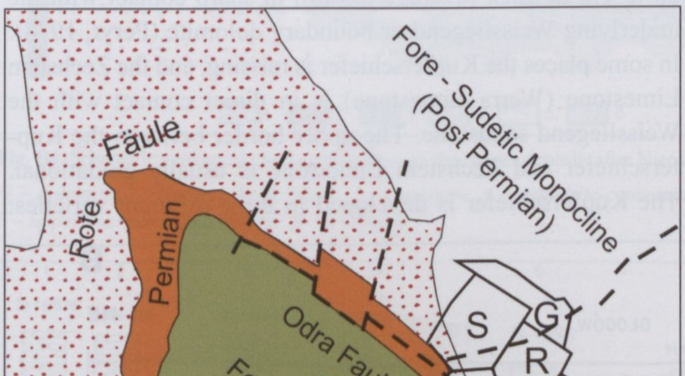


Fig. B1. Simplified map (without Cenozoic strata) of the Fore-Sudetic copper deposit
(L – Lubin Mine; P – Polkowice Mine; R – Rudna Mine; S – Sieroszowice Mine; G – Głogów Deep, perspective area).

Extraction of the copper ores began in Lubin in 1962. Exploitation of Cu ores at the Polkowice Mine began in 1968. In 1972 the mine achieved the planned annual mining capacity of 4,500,000 t of ore. Recently this mine forms a joint unit together with the Sieroszowice mine, that is the youngest mine in the district. The ore is extracted by blasting with dynamite. There are two major systems implemented in these mines: one-layer room and pillar with self back-filling, and two-layer room and pillar with partial back-filling. For the back-filling the barren rock is used, taken from the first extracted layer. The mining field of the Sieroszowice-Polkowice Mine is located in the eastern part of the copper district, and therefore an ore horizon usually has a thickness of less than 2 m. The mining waste and dilution originates mainly from areas of thin deposits of up to 1.5 m where a mining stope required by the transportation vehicles is 1.7 m. The average Cu content in the ore is above 2 wt%. All mining activities are fully mechanized.

Exploitation of copper ores at Rudna Mine started in 1974. Recently it has become the biggest mine in the district, with an annual output above 12,500,000 t of ore. For the whole mining district 29,412,600 t of ore containing 1.64% Cu was extracted in 2008. The Rudna flotation plant also is the biggest in the district, with a daily capacity of 45,000 t. The Rudna ore deposit is located in the central part of the copper district and has the thickest ore horizon. Half of the area reveals thicknesses of more than 7 m. Such thickness requires special extraction systems. In the mine two major systems are implemented. For the ore horizon with the thickness greater than 7 m, a two-layer system is applied. In the first stage the upper layer is extracted followed by the extraction of the lower layer. Subsequently pillars are reduced in volume and sand back-filling is used. For ore horizons less than 7 m thickness, a second system is employed, based on self back-filling with deflection of the hanging wall.

The annual metallic copper production is in the range of 500,000-550,000 t, but only 470,000 t come from the company´s mining production, silver – 1,200 t, gold – 489 kg, Pt+Pd sludge – 70 kg, rough lead – 13,800 t, Co-Cu alloy – 400 t, sulphuric acid – 532,300 t, Cu sulphate – 6,232 t, Ni sulphate – 1,722 t, and technical selenium 67 t. Since 1991 KGHM has also been recognized as a rock salt producer. Permian (Werra) rock salt is extracted from the western flank of the deposit at the Sieroszowice-Polkowice Mine.

Benefaction of ore begins with size classification and disintegration, followed by grinding and grading, flotation with purification of final fractions and dewatering of the concentrate. The whole process is fully mechanized and controlled with chemical analyses within the system. The Rudna concentrate contains above 27 wt% of Cu and is the best in the district. In 2008 the average for the district was 23.0% Cu in the concentrate.

B2. Geological setting

The Lubin–Sieroszowice copper district is located in the south-west part of the Fore-Sudetic Monocline, close to the northern boundary of the Fore-Sudetic Block. The Monocline is composed of Upper Permian to Cretaceous sediments, and it is a part of the Permian sedimentary basin (Fig. B1) (Wyżykowski, 1961; Tomaszewski, 1981; Oberc & Tomaszewski, 1963; Kłapciński, 1971; Krasoń, 1967; Ziegler, 1982; Kłapciński & Peryt, 1996; Rydzewski, 1996). It dips at 3–6° to the north-east. The stratigraphy is shown in Figs. B2 and B6. The basement consists mainly of Proterozoic and early Palaeozoic strata composed of gneisses, schists, phyllites and granitoids. These units are uncomformably overlain by deformed Carboniferous conglomerates, sandstones and mudstones, and subsequently by the Permian strata. Permian rocks are a part of the European Permian sedimentary basin (Peryt & Oszczepalski, 1996; Karnkowski, 1999). Lower Zechstein beds cover the surface of about 100,000 km² (Oszczepalski & Rydzewski, 1987; Oszczepalski, 1989).

The Lower Rotliegend (Autunian) beds are well developed only in the western part of the Fore-Sudetic Monocline (Siemaszko, 1978; Ryka, 1978, 1981; Speczik, 1985; Kłapciński *et al.*, 1988.). They are subdivided into two sequences. The lowermost part, up to 150 m thick, is composed of red-colored conglomerates, sandstones and mudstones. Clastic sediments are capped by bimodal volcanics composed of rhyolites, rhyolitic tuffs and trachybasalts (a few m thick in the central part, up to over 1,000 m in western part) (Juroszek *et al.*, 1981; Speczik, 1985). The Upper Rotliegend beds (Saxonian) are better developed in the western part of the Fore-Sudetic Monocline. The thickness of the Saxonian clastic sediments reaches 700 m in the western part of the Monocline and decreases to 200 m towards the SE. The Saxonian red beds are composed of sandstones and conglomerates. The sandstones are fine to medium grained, partly well sorted, subangular, and contain 70–95% quartz, locally up to 20% feldspars and a matrix composed of clays, carbonate, and locally gypsum and anhydrite.

The uppermost part of the Rotliegend is gray/white and is called Weissliegend. The thickness of the Weissliegend varies from less than 1 m up to 40 m. The contact between Rotliegend and Weissliegend is usually gradational. The uppermost part of the Weissliegend is probably the oldest (first) sediment of the Zechstein sea (Jerzykiewicz *et al.*, 1976; Nemec & Porębski, 1977; Błaszczyk, 1981).

The Basal Limestone, which is named "boundary dolomite" in the mine district, overlies the Weissliegend and is up to 0.3 m thick. It occurs mainly in the south-eastern part of the copper district. It is a sparry to micritic organic-bearing dolomite with minor calcite, locally organogenic.

The Kupferschiefer is a typical black organic-bearing shale, up to 1.2 m thick (average 0.3 m), in sharp contact with the underlying Weissliegend or boundary dolomite (Peryt, 1978). In some places the Kupferschiefer is missing, and the Zechstein Limestone (Werra Limestone) is in direct contact with the Weissliegend sandstone. The upper border between the Kupferschiefer and Zechstein Limestone is usually gradational. The Kupferschiefer is developed in three different varieties:

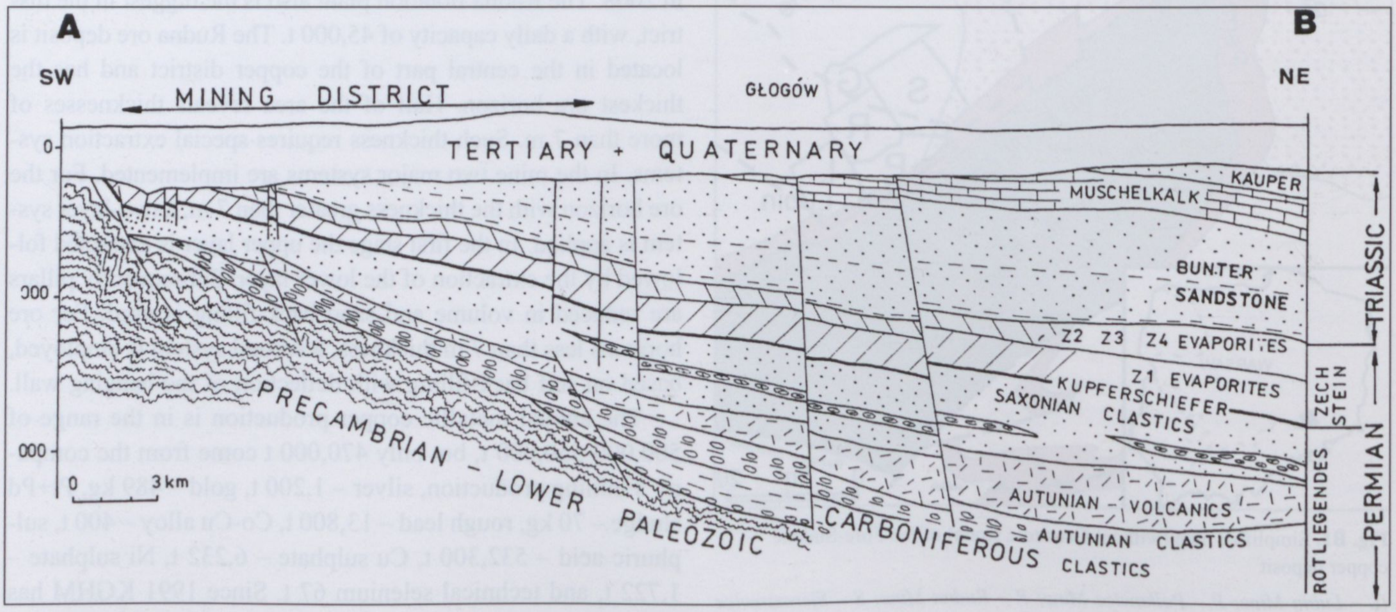


Fig. B2. Geological cross-section through the Fore-Sudetic monocline (after Wodzicki & Piestrzyński, 1994).

organic-rich (pitchy) shale, clayey shale and carbonate-rich shale. The Kupferschiefer is composed of clay minerals (mostly illite), organic matter, carbonates, sulphides, sulphates, and minor terrigenous quartz and feldspar grains.

The Zechstein Limestone (Z1) grades upwards from dolomitic to calcitic composition. The thickness of this unit varies from about 120 m in the coastal facies to 5-10 m in the central part of the Zechstein basin. In the mining district the thickness of Z1 is about 30-40 m. The Zechstein Limestone is covered with the Lower Anhydrite and the oldest rock salt units. Zechstein evaporitic sequence is divided into four cyclothems, which are well developed within a central part of the basin. In the mining area only the cyclothem Z1 is developed. They are overlain by the Triassic red beds and carbonates.

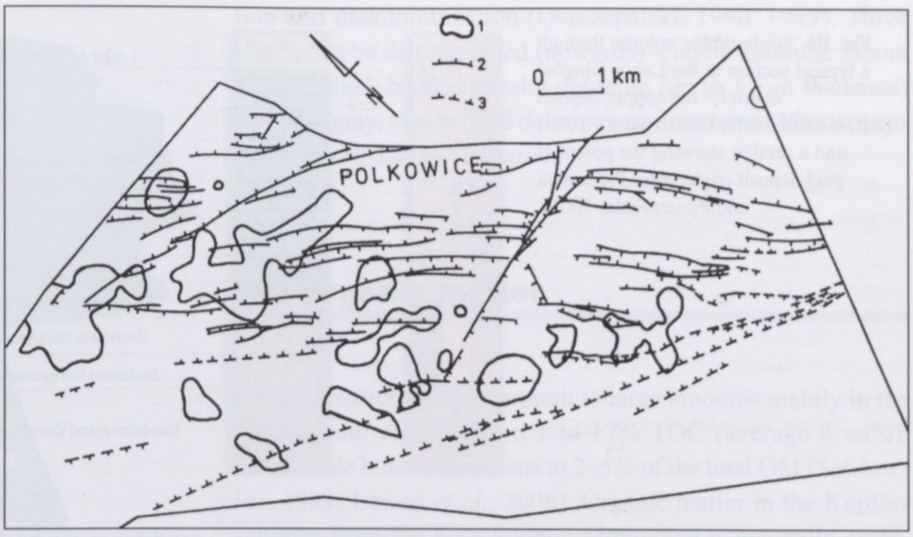


Fig. B3. Schematic tectonic map of the Polkowice Mine (after Salski, 1996) with the location of the richest gold-bearing areas (after Pieczonka & Piestrzyński, 2001)
(1 – areas containing >3 ppm Au; 2 – proven faults; 3 – probable faults).

The Fore-Sudetic Monocline was formed during the Laramian orogeny. Along the southern border the Monocline is separated from the Fore-Sudetic Block by a system of faults called the Odra fault zone (Figs. B1, B2). The Odra fault zone separates Variscan internides and externides. The Fore-Sudetic Block is composed of Precambrian to the Lower Palaeozic metamorphic and crystalline rocks (Kłapciński & Peryt, 1996).

In the Lower Permian a deposition of siliciclastic sediments was associated with dacitic-andesitic Autunian volcanism. Redbed sedimentation was controlled by local morphology and tectonic activity. Large scale epeirogenic and syntectonic movements of separate blocks, accompanied by differentiated morphology of the Lower Permian rocks were the major factors that influenced the deposition of Zechstein sediments. In the Fore-Sudetic Monocline three faults systems NW–SE, W–E and N–S, with offset up to 100 m have been recognized. About 60% of all faults in the ore horizon have an offset of about only 1 m (Salski, 1975, 1996) (Fig. B3).

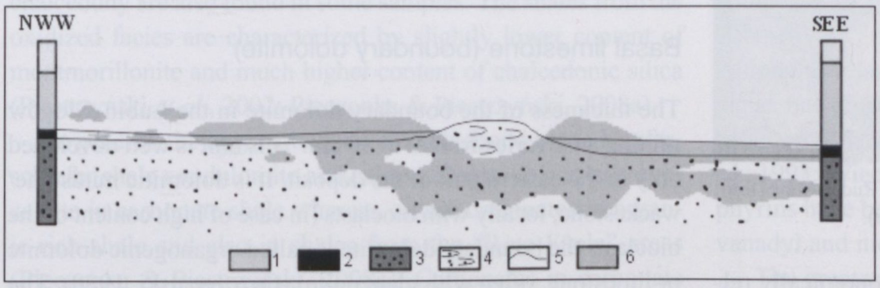


Fig. B4. Schematic geological cross-section through the copper deposit (after Nieć & Piestrzyński, 1996)
(1 – dolomite, 2 – Kupferschiefer shale, 3 – sandstone, 4 – anhydrite-cemented sandstone, 5 – uppermost part of sandstone, 6 – ore body).

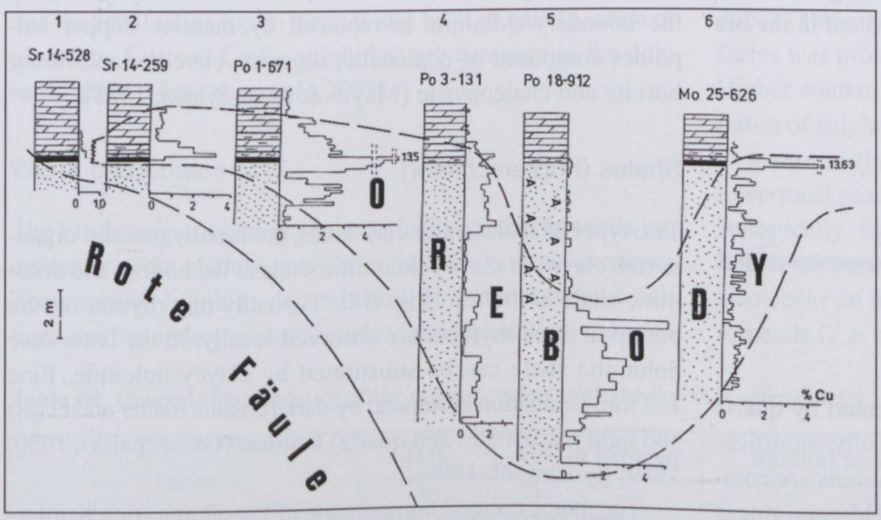


Fig. B5. Lithological sections through the Sieroszowice (1, 2) and Rudna (3, 4, 5, 6) mines, showing quantitative distribution of copper and its relation to the Rote Fâule facies. Column 5 shows a section containing anhydrite-rich sandstone, whereas column 4 is located close to that section (after Wodzicki & Piestrzyński, 1994).

B3. Forms of the deposit

The generally stratoidal ore horizon comprises the lowermost part of the Zechstein Limestone, the Kupferschiefer and the uppermost part of the Weissliegend sandstone (Figs. B6, B7). The shape of the deposit varies from stratiform, peneconcordant to discordant (Fig. B4). The stratiform deposit is restricted to the Kupferschiefer bed. Peneconcordant and discordant types are characterized by the base metal with economic concentrations in the rocks. The main features of ore deposits are summarized in Figs. B5 and B6. The thick-

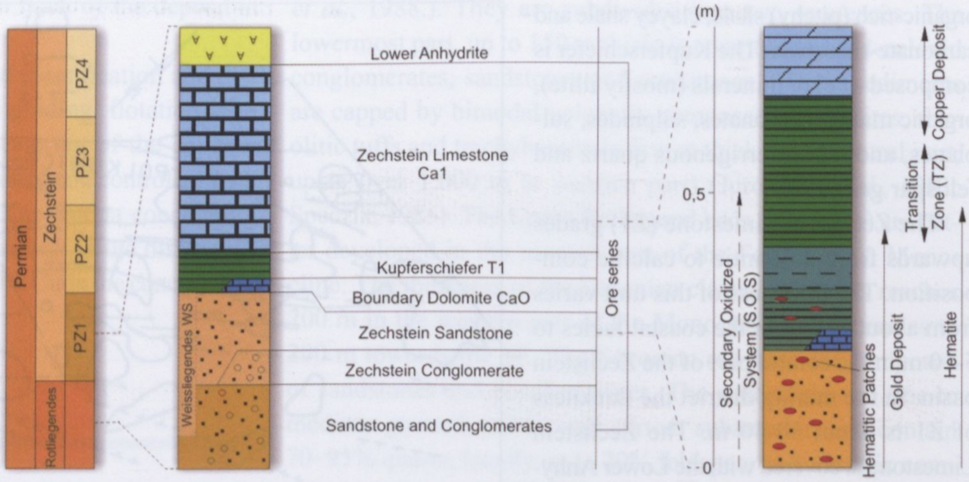


Fig. B6. Stratigraphic column through a typical section in the Lubin-Głogów district – the copper deposit (left, modified after Oszczepalski, 1999) and a section showing the potential gold deposit (right, after Pieczonka and Piestrzyński, 2001).

Fig. B7. Geological profile through a typical section of the Rudna Mine (from the bottom: white sandstone, Kupferschiefer, and dolomite).

ness of the deposits varies from 1 to 26 m. Economically relevant parameters for the deposit are: 50 kg/m^2 of Cu, and minimum content of 1.7% copper in the interval of extracted wall. Cutoff grade for the copper ores is 0.7% Cu. One gram of silver is an equivalent for the 0.01% of copper content in the ore (Nieć & Piestrzyński, 2008) (Fig. B5).

B4. Petrology and mineralogy of the ore horizon

Weissliegend sandstone

The typical sandstone is pale-gray and represented by quartz arenites with a grain size of 0.05–0.2 mm. Locally, stratification is seen due to thin clay laminae. Skeleton grains are composed mainly of quartz (about 75%), minor feldspars, micas and fragments of siliceous, volcanic or locally carbonate rocks (Błaszczyk, 1981; Jerzykiewicz *et al.*, 1976; Nemec & Porębski, 1977, 1981). Numerous diagenetic events in the Weissliegend sandstones can be distinguished and ordered in several sequences resulting in different lithofacies (Michalik, 2001).

Generally the volume of carbonate cement increases towards the top. Locally, especially at the sandstone elevations (sandstone roof elevations, probably palaeodunes), the cement is mainly anhydritic. In the oxidized facies, known as Rote Fäule, especially in German literature, cement is dominated by fine-grained hematite and minor carbonates and clay minerals (Pieczonka *et al.*, 2008a).

Basal limestone (boundary dolomite)

The thickness of the boundary dolomite in the Lubin-Głogów mining area varies from 0 to 30 cm. This unit is well developed only in the eastern part of the deposit. It is dolomitic mudstone/wackestone, locally with bioclasts (in case of high content of the bioclasts the boundary dolomite is called organogenic dolomite or limestone, often with glauconite) (Oszczepalski, 1980). The transition between sandstone and dolomite is usually gradual, although locally it can be sharp, especially where the dolomite is underlain by a thin (several mm thick) shale layer. Locally the boundary dolomite is replaced by massive copper sulphides composed of chalcocite, digenite, covellite and minor bornite and chalcopyrite (Mayer & Piestrzyński, 1985).

Shales (Kupferschiefer)

Two types of shales, rarer clayshales, are usually present: organic-rich clayey or clayey-dolomitic shale at the bottom and dolomitic shale at the top (Fig. B8). Typically one rhythm occurs but up to three rhythms are observed locally. In the latter case dolomitic shale can be substituted by clayey dolomite. Fine 1–2 mm lamination is stressed by dark (organic matter and clays) and light (carbonates and quartz) laminae (Oszczepalski, 1980, 1989; Rydzewski, 1996).

The major mineral components of the organic-rich Kupferschiefer are clay minerals and quartz, carbonates and ore minerals. The main clay mineral present in the organic-rich shale is illite, with some admixture of mixed-layer montmorillonite-

Fig. B8. A typical clayey-carbonate Kupferschiefer (Lubin Mine).

illite. Locally, especially in the East Lubin area, chlorites (up to 20%) and small amounts of kaolinite are also present. All samples with chlorites contain large amounts of pyrite and calcite.

Quartz is present in the Kupferschiefer mainly as dispersed detrital grains, but it also occurs more rarely in small lenses or laminae. Small amounts of oval authigenic grains of quartz or chalcedony are also found in some samples. The shales from the oxidized facies are characterized by slightly lower content of montmorillonite and much higher content of chalcedonic silica (Piestrzyński *et al.*, 2002; Pieczonka & Piestrzyński, 2008a).

In general, the only carbonate minerals found in the Kupferschiefer shale are dolomite and calcite. Dolomite prevails over calcite in carbonate shale whereas calcite dominates in organic-rich shale and also in shales from the "Rote Fäule" areas (Pieczonka & Piestrzyński, 2008a). Carbonates in carbonate shale form thin regular laminae, often with admixture of clay minerals. In organic-rich shale carbonates form small lenses, irregular veinlets or are dispersed in clay laminae. Horizontal and diagonal veins (up to 5mm wide) built of calcite, often replaced by Cu- and Cu-Fe sulphides, are common in the dolomitic shale (Gawecka *et al.*, 2003).

Werra carbonates (Z1)

The black copper-bearing shale typically grades upwards into carbonate rocks, mainly mudstones, but also rarer wackestones. Their various lithology depends both on sedimentation conditions and secondary changes such as dolomitization, calcitization and dedolomitization (Oszczepalski, 1980, 1989). Three layers can be distinguished (upwards): clayey dolomite (about 40 cm), thick-bedded streaky dolomite (up to 1.5 m thickness) and light gray, thin-bedded dolomites or limestones. Micrite generally dominates over sparite.

B5. Organic matter

Organic matter (OM) is present in large amounts mainly in the black shale, varying from 1 to 17% TOC (average 6 wt%). Extractable bitumen amounts to 2–5% of the total OM (Sawlowicz, 1989; Lewan *et al.*, 2008). Organic matter in the Kupferschiefer from the Fore-Sudetic Monocline is generally amorphous (liptinite-type), occurring mainly in the form of irregular laminae and lenses, 1 to 100 μm thick. It commonly envelopes sulphide grains. Reflectance of rare vitrinite from the organic laminae has a strong maximum around 0.6–0.8%, suggesting temperatures not higher than 100 °C (Speczik & Püttmann, 1987; Speczik 1994; Nowak *et al.*, 2001). Marine organisms were the main source of the Kupferschiefer organic matter, as evidenced by amorphous kerogen of type II (with admixture of type I), *n*-alkane composition, carbon isotopes, C/N and H/C ratios (Sawlowicz, 1993a; Lewan *et al.*, 2008). Among the several groups of organisms (phytoplankton, algae, bacteria) the most plausible seems to be algae. The contribution of terrestrial material is generally low (Rospondek *et al.*, 1993; Więcław *et al.*, 2007). Several different metalloporphyrins have been identified in the Polish Kupferschiefer, *e.g.*: vanadyl and nickel porphyrins (Sawlowicz, 1985).

The greatest differences in the organic matter are between mineralized areas and that of secondary oxidized hematite-bearing Rote Fäule (RF) barren facies (Püttmann *et al.*, 1989; Sawlowicz, 1993a; Sawlowicz *et al.*, 1999; Więcław *et al.*, 2007) (Table 1). The original content of OM in the Rote Fäule facies was probably close to that of highly mineralized shales. Higher content of sulphur in OM may result from the incorporation of sulphur from oxidized sulphides. Oxidation of organic matter in the Rote Fäule areas, and to some extent in the lowermost part of the Kupferschiefer, results in the release of isotopically light carbon and is expressed by isotopically lighter carbonates in these samples. The oxidation processes also occur on microscopic scales at the contacts with different minerals (*e.g.* thucholite and noble metals).

Table B1. General characteristics of the organic matter from the Polish Kupferschiefer

Facies	TOC	H/C in kerogen	Sulphur in asphaltenes	Ph/ΣMePh	R_o vitrinite
	%		%		%
Ore-bearing shale	4.2-17.7	0.84-0.97	1.7-2.8	0.7-1.1	0.5-0.9
Oxidized shale – Rote Fäule	1.5-5.8	0.41-0.49	3.1-4.4	2.0-2.4	0.9-0-1.1

The OM plays one of its most important roles in the mineralizing process in the Kupferschiefer during bacterial sulphate reduction (BSR), which was the major process producing the sulphur for metal sulphide formation. A surplus of bacteriogenic sulphur could be bound to the labile organic sulphur compounds (OSC), as suggested by residual benzothiophenes and dibenzothiophenes. The release of sulphur from the OSC during diagenesis and catagenesis has been suggested to be one of the mechanisms of ore mineralization in the Kupferschiefer, particularly in the case of the very rich ores in the Weissliegend sandstones underlying the Kupferschiefer (Rospondek *et al.*, 1994). Some authors have suggested that the source of reduced sulphur was a thermocatalytic reduction of sulphates (TRS) from basinal brines at high temperatures. However, the process of TRS seems to be of little importance at temperatures below 100° C, as is the case in the Kupferschiefer.

Fig. B9. Massive copper sulphide mineralisation in the topmost part of the white sandstone from the Weissliegend elevation in the Rudna Mine.

B6. Ore mineralisation

Over 140 ore minerals have already been identified within the copper district. Chalcocite is the dominant ore mineral and locally it can constitute up to 90 vol% of the rock, *e.g.* in massive sandstone ores (Figs. B9, B10). The copper ores are also characterized by significant amounts of bornite, chalcopyrite, digenite, covellite, galena, sphalerite, pyrite, tennantite and tetrahedrite. Ore minerals usually have xenomorphic shapes. In the mining district the following types of ore mineralisation can be distinguished: dispersed, nests, lenses, ore bands, veinlets and veins, and massive (Piestrzyński, 2008 and references. therein). In a completely developed ore horizon, the highest contents of Cu and Ag occur typically in the shales (see Fig. B14 below).

Fig. B10. Massive nest-like Cu-S mineralization in the Weissliegend (Rudna Mine).

Dispersed mineralisation dominates in all types of ores: sandstones, shales, and carbonates. It can be found in all stages of mineralization processes, being the most important during the early stages. Pyrite, chalcocite, cobaltite and bornite framboids are common here.

Nest-type mineralisation is very common in carbonate ores, and rare in the sandstone. Nests are composed of copper sulphides, carbonates and sulphates in the ore horizon. In the subgrade ores, sphalerite, galena, pyrite, and marcasite also occur. This type is clearly visible macroscopically.

Lensoidal structures are common in shale and carbonate ores. Ore minerals often replace organic remnants of brachiopoda, foraminifera, and ostracoda. Sulphide pseudomorphs after lensoidal francolite are also observed in the shale horizon.

Thin (1 cm) ore bands are observed only in the sandstone ores. Ore bands occur about 1 m below the Kupferschiefer, and are usually developed parallel to the top of the sandstone strata. The number of ore bands varies from place to place and can reach 60. Ore bands or rhythmites are very regular in the shape (see Fig. B22 below).

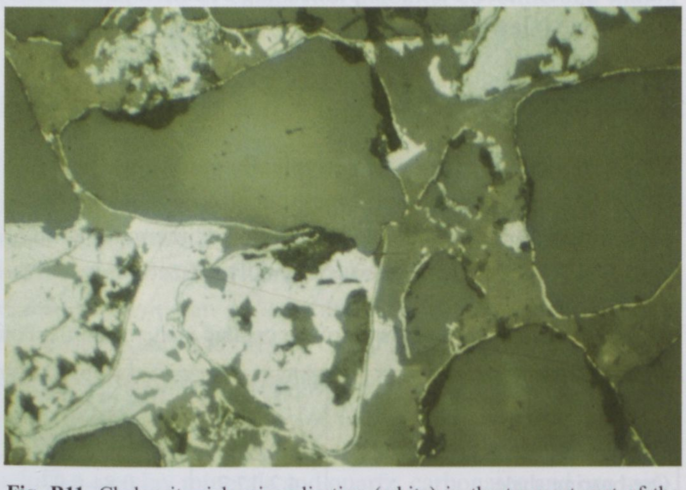


Fig. B11. Chalcocite-rich mineralisation (white) in the topmost part of the white sandstone. Chalcocite replaces feldspar grains and clay coatings on detrital grains, Rudna Mine (reflected light, width of photo is 0.5 mm).

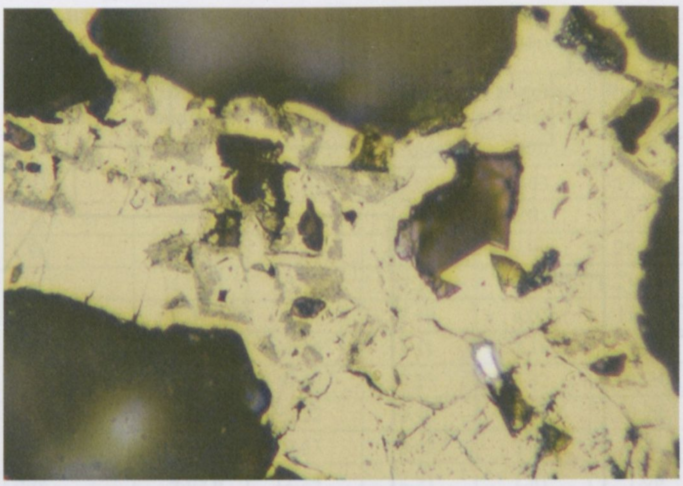


Fig. B12. Chalcopyrite (yellow) replaces diagenetic rhombohedral dolomite in the white sandstone (Rudna Mine; reflected light, width of photo is 0,5 mm).

Massive mineralisation is typical for the sandstone ore and is classified as late diagenetic. It can be observed in the uppermost part of the Weissliegend and in the contact zones with the anhydrite-cemented sandstone. Locally chalcocite replaces all constituents of sandstone, forming massive copper ore containing up to 90 wt% of chalcocite (Figs. B11, B12). Massive forms of ore minerals, mostly chalcocite, are also observed in the boundary dolomite. There is no spatial relationship with the vein-type mineralisation.

Veins and veinlets are very common in the shale horizon (Fig. B13), and sometimes in the clayey dolomite. Veinlets (up to 1 cm thick) are typical for the shale and have developed both parallel and diagonal to the shale lamination. They are composed exclusively of base metal sulphides.

Wide veins (usually 5–15 cm, sometimes up to 1.2 m wide) are rare and cut vertically or diagonally through dolomite and sandstone. They are composed of gangue and sulphide minerals in different proportions and represent late stages of mineralisation, probably associated with Alpine tectonic activity. Some veins contain Ni, Co, Ag, U minerals (Rücken type) (Piestrzyński *et al.*, 2000). This type of mineralisation is not of economic importance.

B7. Mineral zonation

Horizontal and vertical distribution of ore minerals is widely discussed in the literature (Oszczepalski, 1989; Oszczepalski & Rydzewski, 1987; Pieczonka *et al.*, 2007). The central part of the deposit is comprised mainly of Cu-(Fe)-S minerals, whereas these sulphides are accompanied by sphalerite and galena in the eastern and north-eastern part of the deposit (Pieczonka *et al.*, 2007). At the mine scale there is also a vertical zonation. The general mineral distribution is (from bottom to top): pyrite – chalcopyrite – bornite – chalcocite – bornite – chalcopyrite – galena – sphalerite – pyrite. The specific zones often overlap (Fig. B15).

Fig. B13. Two types of ore mineralisation: horizontal (chalcocite) and vertical (bornite and chalcopyrite) in the clayey variety of the Kupferschiefer (Rudna Mine)

Fig. B14. A typical distribution of Cu and Ag in the vertical section from the Lubin Mine

1 – sandstone, 2 – boundary dolomite, 3 – pitchy shale, 4 – clayey-carbonate shale, 5 – clayey dolomite, 6 – dolomite.

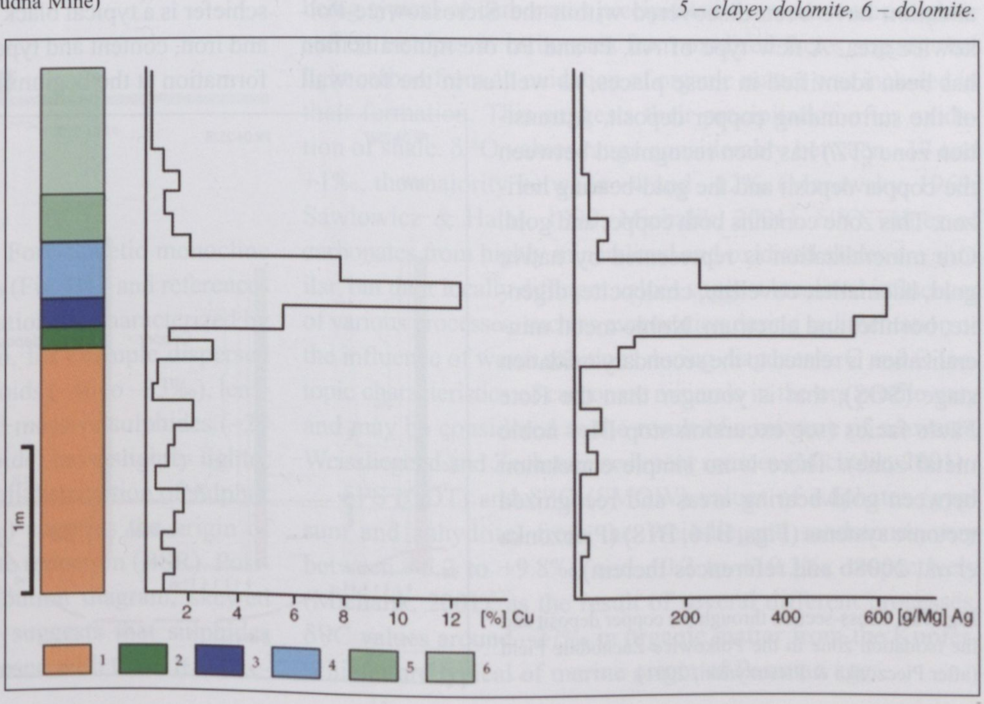
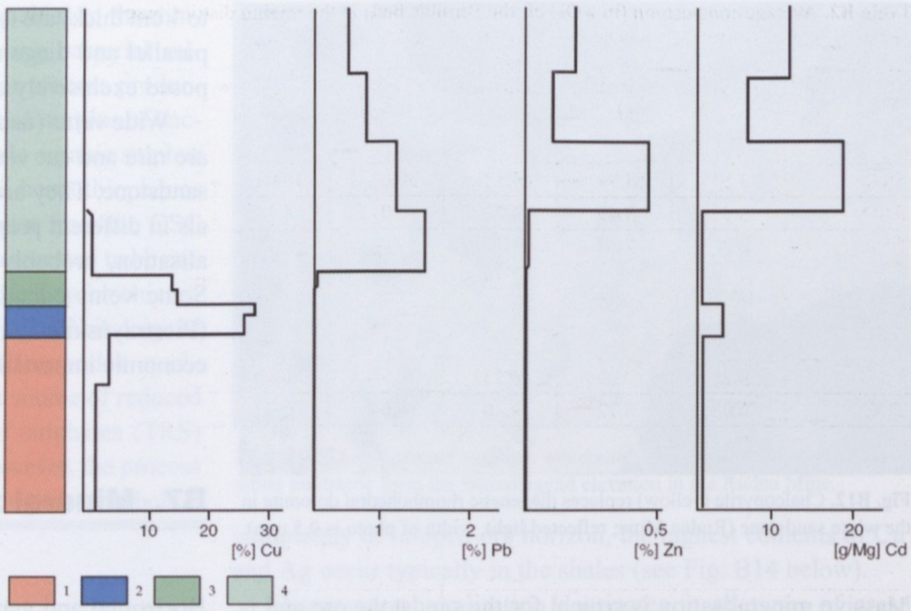


Fig. B15. A typical distribution of Cu, Zn, Pb and Cd in the vertical section from the Sieroszowice Mine
1 – sandstone, 2 – shale, 3 – clayey dolomite, 4 – dolomite.



B8. Barren areas and their economic potential

Within the copper district there are several restricted oxidized areas (Rote Fäule = RF), without an economic copper grade. The biggest of these areas is located in the eastern part of the Polkowice-Sieroszowice Mine (Fig. B1). Copper deposits in the vicinity of the Rote Fäule are distinctly thinner and are developed mostly in the Kupferschiefer and Zechstein Limestone units. The thickness of ore zone is usually below 2 m. The physical border between the Rote Fäule and copper deposit is very complex and often poorly visible at macroscopic levels. It can usually only be determined using chemical analyses.

Several other "barren" areas with no economic copper mineralization have been discovered within the Sieroszowice-Polkowice area. A new type of Au, Pt and Pd ore mineralization has been identified in these places, as well as in the footwall of the surrounding copper deposit. A transition zone (TZ) has been recognized between the copper deposit and the gold-bearing horizon. This zone contains both copper and gold. Ore mineralization is represented by native gold, haematite, covellite, chalcocite, digenite, bornite, and electrum. Noble metal mineralization is related to the secondary oxidation stage (SOS), that is younger than the Rote Fäule facies (see excursion stop BI – noble metal zone). There is no simple correlation between gold-bearing areas and recognized tectonic systems (Figs. B16, B18) (Pieczonka *et al.*, 2008b and references therein).

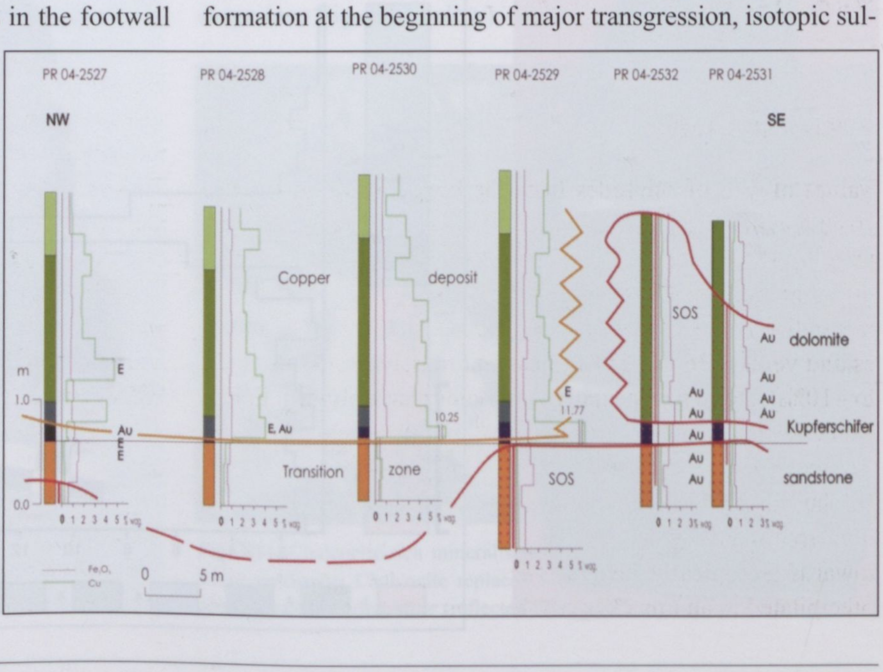


Fig. B16. Cross-section through the copper deposit and the oxidation zone in the Polkowice Zachodnie Field (after Pieczonka & Piestrzyński, 2001).

B9. Geochemistry

The content of the main elements and metals is presented in Table 2. The distribution of metals varies significantly between lithological types of ore (typically the shale ore is the most rich in metals), and between the specific mining fields. Apart from copper the main metals recovered are: Ag, Pb, Zn, Ni, Au, Co, Mo, V and Re (Kucha, 1990).

A number of gangue minerals are enriched in the main metals. Detrital feldspars may contain up to 1–2% of Cu, Zn and Pb, and potassium micas up to 6% of Cu. Organic matter can be locally significantly enriched with many trace elements such as U, REE, Bi, and noble metals (Kucha, 1981).

It is important to stress that in many respects, the Kupferschiefer is a typical black shale, including the content of sulphur and iron, content and type of organic matter, sedimentation rate, formation at the beginning of major transgression, isotopic sul-

Table B2. Average composition (in wt%) of the Permian beds in the mining district, based on the data of KGHM Polska Miedź S.A. (after Kucha & Mayer, 1996)

	Barren sandstone	Anhydrite sandstone	Sandstone ore	Kupfer-schiefer ore	Dolomite ore	Barren dolomite
n	15	49	150	270	196	35
SiO_2	73.53	63.84	69.82	30.63	19.03	15.62
Al_2O_3	3.90	3.49	4.22	10.01	6.18	4.32
CO_2	5.00	2.89	6.50	9.90	29.16	30.21
CaO	6.97	10.42	7.34	7.94	21.93	26.22
MgO	2.24	0.94	2.19	4.05	11.76	10.97
K_2O	1.09	1.36	1.11	2.18	1.34	0.89
Na_2O	0.29	0.69	0.25	0.32	0.29	0.25
TOC	0.08	0.12	0.40	8.04	0.72	0.36
S_s	0.87	0.53	0.82	2.64	0.71	0.74
S_{SO3}	4.09	12.54	2.91	1.81	1.68	3.63
FeS_2	0.26	0.18	0.19	0.66	0.54	0.55
FeO	0.38	0.25	0.62	0.49	0.48	0.43
Fe_2O_3	0.70	0.37	0.53	1.01	0.74	0.83
MnO_2	0.08	0.07	0.16	0.15	0.29	0.23
Cu	0.57	1.88	2.67	10.48	2.10	0.53
Zn	0.0022	0.002	0.04	0.078	0.03	0.09
Pb	0.015	0.021	0.05	0.41	0.14	0.39
Ag [g/Mg]	39	19	29	186	58	50
Ni [g/Mg]	48	24	46	278	60	60
Co [g/Mg]	31	11	19	189	40	40
V [g/Mg]	45	51	59	1204	120	70
Mo [g/Mg]	6	8	40	255	30	10

n – number of analyses

phur composition of sulphides similar to that of pyrite formed in an open system. However, it does exhibit unusually high content of copper, lead and zinc (and arsenic). Enrichment of REE in oxidized facies and their distribution suggests that mineralizing solutions entered the Kupferschiefer horizon from below.

B10. Isotopes and dating

Sulphur isotopes

Values of $\delta^{34}S$ of sulphides from the Fore-Sudetic monocline cover a wide range, from –46 to –10‰ (Fig. B17 and references therein). Different forms of mineralization are characterized by different sulphur isotope composition, for example dispersed mineralization of spherules and framboids (–46 to –33‰), lenses and veins (–36 to –25‰), nest and massive sulphides (–28 to –10‰). Pyrites (especially framboids) have slightly lighter isotopes than copper sulphides. Overall distribution of sulphur isotopes (majority around $\delta^{34}S$–33‰) suggests the origin of sulphur through bacteriogenic sulphate reduction (BSR). Position and shape of the isotope distribution diagram, skewed towards isotopically heavier values, suggests that sulphides precipitated in an open system that closed with time. It is likely that there was an addition of sulphur from other sources, *e.g.* Rotliegend sulphates from the underlying Rotliegend sedimentary basin which are characterized by lower, in comparison with the Zechstein ones, $\delta^{34}S$ values (Amthor & Okkerman, 1998). The range of $\delta^{34}S$ values determined in sulphates of the Weissliegend sandstones corresponds to values recorded in the Rotliegend (Michalik, 2001).

If BSR in a closing system was a major mechanism of sulphide precipitation, then the following succession can be proposed (based on different forms of mineralization in one of the paleodunes and its surrounding deposit, *e.g.* Fig. B21):

- rhythmites in the Weissliegend (av. –40‰)
- finely dispersed small grains and framboids in shale and below in dolomitic sandstone (av. –33‰)
- lenses and veinlets in shale (av. –26‰)
- infiltrations and thick strata along and below the dolomitic sandstone bed in Weissliegendes (av. –21‰)
- spots and rings in sandstones (av. –17‰)
- epigenetic veinlets and strings in sandstone and dolomite (av. –14‰)

Carbon and oxygen isotopes

Values of $\delta^{13}C$ (PDB) of carbonates in the Kupferschiefer shale and the sandstones and carbonate of the ore horizon range between –4.2 and +4.7‰ (Marowsky, 1969; Sawlowicz & Halas, 1990; Michalik, 2001). Generally $\delta^{13}C$ values are around 0‰, being typical of carbonates precipitated from sea water. Lighter carbon isotopes in carbonates from oxidized facies suggest that light carbon from an oxidation of organic matter was included in their formation. This suggests their precipitation after oxidation of shale. $\delta^{18}O$ values range considerably between –17 and +1‰, the majority between –4 and –12‰ (Marowsky, 1969; Sawlowicz & Halas, 1990; Michalik, 2001). $\delta^{18}O$ values of carbonates from highly mineralized and oxidized shales are similar, but their locally different values suggest localized influences of various processes, such as evaporation during sedimentation or the influence of warm solutions during diagenesis. C and O isotopic characteristics of carbonate minerals in the ore profile vary and may be considered as the result of a mixture of seawater, Weissliegend and Zechstein sediment sources (Michalik, 2001).

$\delta^{34}S$ (CDT) and $\delta^{18}O$ (SMOW) values of sulphates (gypsum and anhydrite) from the Weissliegend sandstones vary between +5.2 to +9.8‰, and +0.2 to +10.3‰, respectively (Michalik, 2001), as the result of several different processes. $\delta^{13}C$ values around –27‰ in organic matter from the Kupferschiefer are typical of marine origin of Permian age.

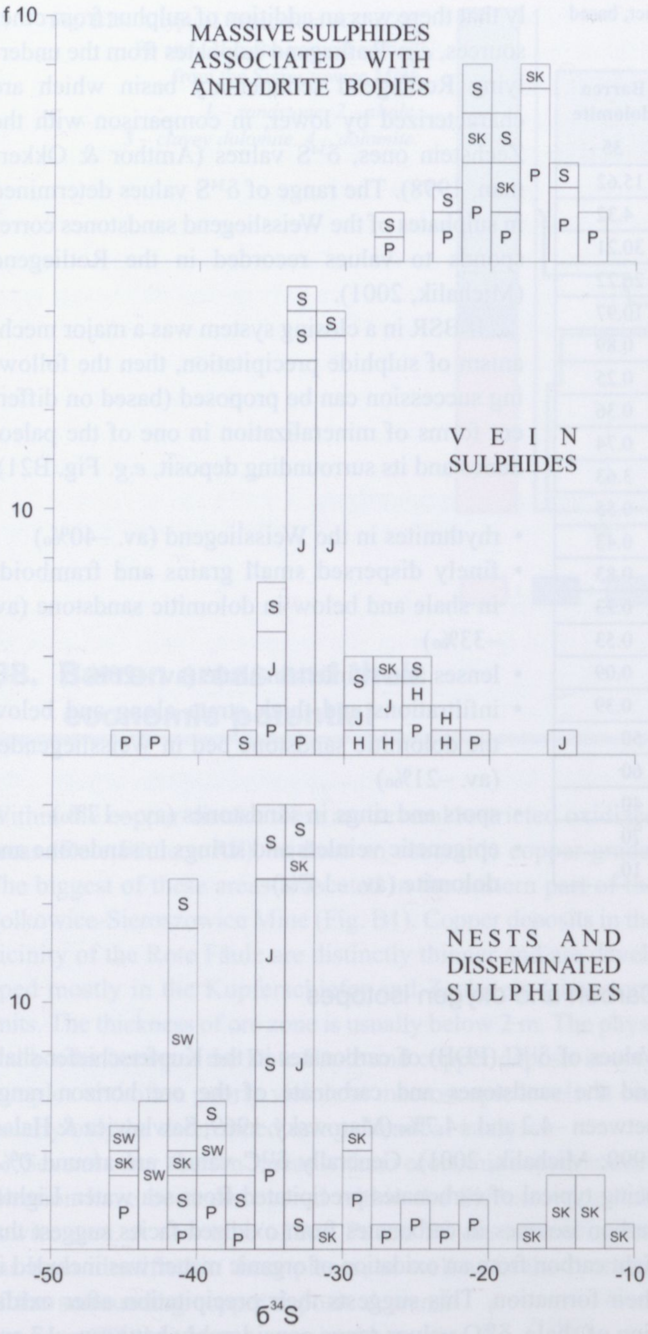


Fig. B17. $\delta^{34}S$ distribution of sulphides from the Fore-Sudetic copper deposit
J – Jowett et al., 1991, H – Haranczyk, 1972, P – Wodzicki & Piestrzyński, 1994, S – Sawlowicz, 1989, SK – Sawlowicz & Kosacz, 1995, SW – Sawlowicz & Wedepohl, 1992

Dating

The Pb isotopic composition of galena ($^{206/204}Pb = 18.790$, $^{207/204}Pb = 15.620$ and $^{208/204}Pb = 38.417$) from the German Kupferschiefer may indicate Precambrian rocks or Precambrian detritus in younger rocks as the lead source (Wedepohl *et al.* 1978).

Remnant magnetization from the hematite in Rote Fäule gives a palaeomagnetic age of 230–240 Ma (Jowett *et al.*, 1991), although it is not possible to correlate distinct morphological type of several haematites with the age of crystallization.

K-Ar dating on illites from the Kupferschiefer give values of 250 Ma for the mineralized shales and 277 Ma for non-mineralized (oxidized?) shales (Bechtel *et al.*, 1995). K-Ar dating by Michalik (2001) indicate that authigenic illite, formed before massive sulphide ores in the Weissliegend sandstones in the Fore-Sudetic Monocline were crystallized over a time span of 188–159 Ma (~Middle Jurassic).

The age of thucholite formation in the Kupferschiefer determined by Kucha and Przybyłowicz (1999) varies between 175 and 180 Ma, This is similar to numerous K/Ar ages of authigenic illite from different parts of the European Rotliegend basin (see Michalik, 2001).

B11. The origin

Controversies about the genesis of the Kupferschiefer copper deposits cover a syngenetic to epigenetic interpretation and are centered mainly on a specific type of mineralization. However, these deposits contain several different types of ore mineralisation, each of which can be dominant in various lithologies and geological periods, and even mining areas. Several stages of the mineralizing process have been proposed (*e.g.*: Jowett, 1986; Kucha & Pawlikowski, 1986; Vaughan *et al.*, 1989; Speczik, 1993; Wodzicki & Piestrzyński, 1994; Oszczepalski, 1999; Michalik & Sawlowicz, 2001; Blundell *et al.* 2003). The importance of each stage varies between the views of the researchers. However, it can safely be stated that multistadial mineralizing processes in the Lubin-Głogów district could span the period from early Zechstein (dispersed mineralisation in shales) to Late Jurassic (massive ores in the Weissliegendes). A mixing of oxidizing metal-bearing fluids from the underlying rocks with reduced sulphur in the reducing Kupferschiefer shale is probably the best explanation for the deposition of sulphides.

The first important stage in the Kupferschiefer deposit formation was syn- and early diagenetic dispersed sulphide mineralisation. In the organic-rich shale, where content of copper and TOC can be as high as 25 and 17 wt%, respectively, this type of mineralisation can constitute up to 30–70 vol% of the total mineralisation. In the shale it is represented by framboids and microspherules (5–10 µm) and their aggregates, often recrystallized into grains (50–100 µm). In Weissliegend sandstone fine copper sulphides form cement in the sulphide rhythmites. Several arguments have been put forward to stress the importance of these early stages: 1) very light sulphur isotopic composition of dispersed sulphides characteristic for bacterial sulphate reduction in an open system; 2) the presence of primary copper sulphide framboids; 3) replacement of iron monosulphide framboids by copper sulphides; 4) low-temperature leaching of copper from copper sulphides as the result of oxidation by Zechstein seawater; 5) probably very early formation of cobaltite-pyrite framboids; 6) some syn-sedimentary conglomerates com-

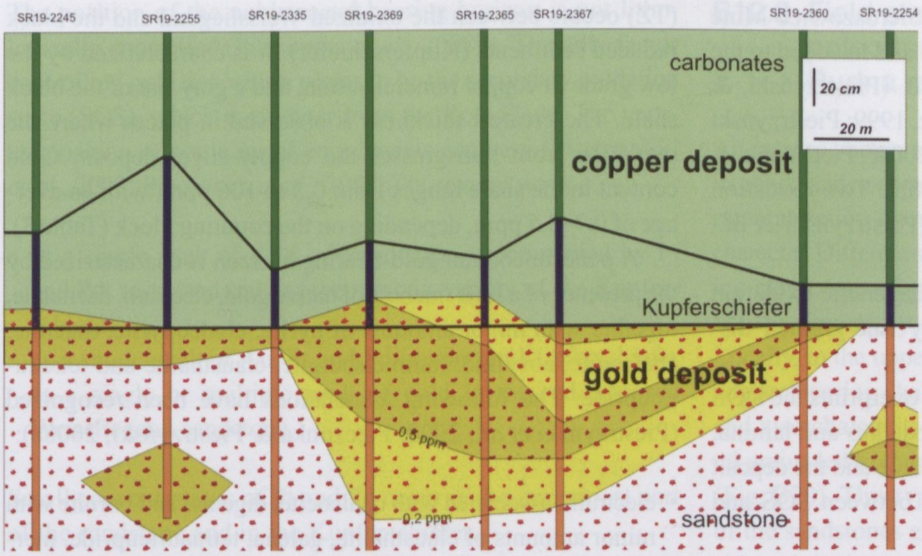


Fig. B18. Cross section through the partly oxidized section in of the Polkowice Mine, containing gold (red dots show oxidation zone, green - copper deposit located in shale and dolomite, white – sandstone, yellow – gold deposit).

Fig. B19. Different types of red spots and patches from the oxidized section from the Polkowice Mine (uppermost two photos are white sandstone, the remaining ones are boundary dolomite).

prise shaly clasts mineralized by sulphides before their erosion; 7) characteristic early-diagenetic bending of clay-organic lamina around dispersed sulphide forms.

Weissliegend sandstones containing massive sulphide cementation (a high-grade ore) are an example of late stage mineralization. Determination of the time relationships between formation of dispersed sulphides and other diagenetic events is difficult but can be done in the case of massive sulphide crystallization. In the high-grade ores the massive sulphide cements replace both framework grains and authigenic illite and other cements. This cement replaces also coarse-crystalline calcite, which post-dates authigenic illite. K-Ar dating of authigenic illites allows the lower time limit of massive ores to be placed in Late Jurassic (Michalik, 2001).

There is general agreement as to the origin of mineralizing fluids. Oxidized chlorine-rich brines formed in the underlying thick molasse rocks (also containing some volcanics) and perhaps the basement, and entered the Kupferschiefer sulphide-rich bed probably at the Rote Fäule areas. The expulsions were possibly a result of a combination of periods of high heat flow and faulting (Blundell *et al.* 2003).

B12. Selected mine stops

B12.1 Field stop B1: Noble metals in oxidized zones – Polkowice-Sieroszowice mine

The noble metals have been investigated since the early 1980s. High concentrations of noble metals have been described from a very local and thin (from a few μm to cm) layer at the base of the Kupferschiefer by Kucha (1982). Significant enrichment of Au and PGE (10 to 100 times) in bulk samples from oxidized facies (Rote Fäule = RF) present inside the mining area (Sawlowicz, 1993b) stimulated an exploration for economically important accumulations of these metals. Current studies in the Polkowice-Sieroszowice Mine have significantly extended our knowledge and have led to the description of the potential gold deposit (Piestrzyński & Pieczonka, 1997; Piestrzyński & Sawlowicz, 1999; Piestrzyński & Wodzicki, 2000; Piestrzyński *et al.*, 2002; Pieczonka & Piestrzyński, 2008a; Pieczonka *et al.*, 2008b). Two oxidation stages can be recognized in that deposit (Piestrzyński *et al.*, 2002; Pieczonka & Piestrzyński, 2008b):

Rote Fäule "facies", represented by a diagenetic oxidation stage (DOS). The RF is characterized by fine-grained dispersed haematite.

A secondary oxidation stage (SOS) that overprints the DOS (Fig. B19). It is characterized by maroon patches and lamina, and is peneconcordant relative to the Rote Fäule and the deposit lithologies. There is a strong relationship between SOS and the occurrences of noble metals.

Underground prospecting within the Lubin – Sieroszowice mining area that has taken place during last 7 years has led to the discovery of a new type of gold mineralisation located 0–0.5 m below the copper-silver ore body (Figs. B16, B18). The thickness of the gold deposit varies from a few cm to 1.5 m. It is located mainly in the Weissliegend sandstone, but locally transgresses the stratigraphic sequence into the overlying Kupferschiefer and even Zechstein Limestone, and is related to the red-coloured SOS stage (Fig. B19). A transition zone (TZ) occurs between the oxidized Weissliegend and the black reduced sediments (Kupferschiefer). It is characterized by the low grade of copper mineralisation, and a gray tint of the black shale. The greatest thickness is observed in places where the oxidation front transgresses the copper-silver deposit. Gold content in the shale ranges from 0.5 to 106 ppm, with an average of 0.7–3.5 ppm, depending on the counting block (Table 3).

A peneconcordant gold-bearing horizon is characterized by the presence of a high fineness of native gold, electrum, haematite, together with minor amounts of pyrite, chalcopyrite, digenite, chalcocite, covellite, rammelsbergite, clausthalite and tetraauricupride. The following associations have been recognized (Piestrzyński *et al.*, 2002; Pieczonka & Piestrzyński, 2008a):

- electrum, associated with chalcocite, digenite and bornite with minor amounts of clausthalite, galena, tetraauricupride, mercury-bearing electrum, spionkopite, yarrowite and tiemannite
- native gold associated with hematite and covellite, containing gold of high purity, ranging between 92 and 96 wt%.
- Microprobe analyses also show significant gold content in hematite, bornite and chalcocite.

The vertical distribution of noble metals is shown in Fig. B16. In all sections analyzed, the noble metal concentrations are present only in those parts of profiles that are barren in copper.

Table B3. Chemical composition of the selected gold-bearing rocks in the Polkowice Zachodnie Field (after Piestrzyński *et al.*, 2002)

		red sandstone PZ/G31/1	maroon shale PZ/G31/2	maroon shale PZ/G31/5	maroon shale PZ/G31/6	maroon shale PZ 21/1	maroon shale PZ 22/1	grey shale PR18-I	grey shale PR18-II	grey shale PZ/G31/3
SiO_2	%	64.99	16.78	51.28	48.94	19.72	31.04	28.30	25.25	46.18
Al_2O_3	%	2.74	6.03	21.18	18.70	6.96	10.71	10.94	10.32	16.73
FeO	%	≤0.17	≤0.17	0.18	0.09	≤0.05	≤0.05	0.54	1.08	≤0.17
Fe_2O_3	%	2.14	6.01	6.56	8.76	5.13	5.14	1.50	1.24	2.22
MnO	%	0.30	0.49	0.04	0.08	0.36	0.37	0.38	0.29	0.19
MgO	%	1.45	11.88	2.57	3.17	11.87	8.08	5.47	4.23	3.87
CaO	%	13.94	23.39	1.23	2.87	21.73	16.65	22.10	25.96	8.37
Na_2O	%	0.08	0.19	0.96	0.57	0.22	0.29	0.11	0.11	0.27
K_2O	%	1.23	1.89	6.18	5.69	1.96	3.58	3.23	2.92	4.95
TiO_2	%	0.07	0.26	0.91	0.86	0.31	0.50	0.47	0.39	0.87
P_2O_5	%	0.04	0.09	0.14	0.14	0.24	0.22	0.10	0.09	0.22
TOC	%	≤0.1	≤0.1	0.44	0.41	0.08	0.11	1.29	0.72	1.67
$C_{carb.}$	%	3.87	8.85	0.54	0.52	n.a.	n.a.	7.77	9.95	3.27
Se	ppm	≤3.0	5.0	≤3.0	≤3.0	≤0.3	≤3.0	14.0	≤3.0	42.0
Au	ppm	14.30	0.11	0.11	0.09	94.90	17.30	2.28	12.60	0.70
Cu	ppm	76	2264	51	29	2102	797	963	784	537
V	ppm	48	435	1561	1200	434	495	1156	1115	1461
Th	ppm	1.8	5.7	12.9	12.4	9.6	6.3	7.2	7.7	14.5
U	ppm	1.7	15.6	7.3	7.5	9.9	10.2	12.7	18.5	17.5

n.a. – not analysed
Sample PZ/G31/1 – gold-bearing sandstone; samples PZ/G31/2, PZ/G31/5 and PZ/G31/6 – barren Rote Fäule; samples PZ/21/1 and PZ22/1 – gold bearing horizon of the secondary oxidation stage; samples PR18-I, PR18-II – transition zone.

The position of the noble metal-bearing horizon is not lithologically controlled (Pieczonka *et al.*, 2008b). The only factor controlling gold deposition seems to be the secondary oxidation stage (SOS), which is younger from the Rote Fäule. The vertical position of noble metal enrichments can vary (Piestrzyński *et al.*, 2002; Pieczonka *et al.*, 2008b) in several ways:

- as a single peak of gold in carbonates, accompanied by Pt and Pd, restricted only to the maroon variety of the Kupferschiefer
- as a single peak of Au, Pt and Pd in maroon Kupferschiefer
- as a single or multiple peak of gold in the red-coloured Weissliegend sandstone.

Small concentrations of Pt and Pd occur in the uppermost part of the sandstone and in the Kupferschiefer.

The horizontal distribution of the redbed gold deposit is not fully documented. It is a zone at least 6 km wide. Only the northern border is well described, whereas the southern border has not yet been established because of the limited extent of the mining works.

The described gold-bearing zone can be classified as a redbed-related Au-deposit. The genetic model is similar to volcanogenic redbed copper and uranium roll-front types, the redox boundary extending mainly horizontally. The Lower Permian molasse was probably the source of oxidizing fluids containing gold. Rapid oxidation of iron and organic matter present in the copper horizon caused gold reduction and simultaneous crystallization of coarse-grained hematites (Pieczonka & Piestrzyński, 2008b).

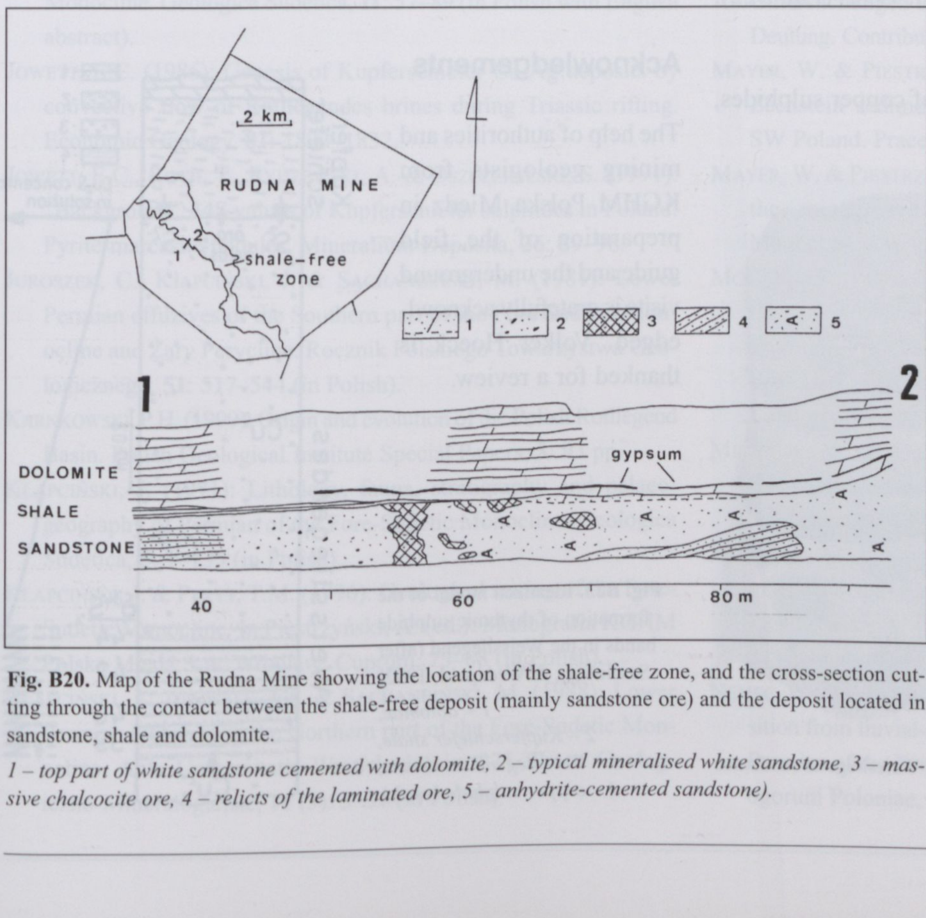


Fig. B20. Map of the Rudna Mine showing the location of the shale-free zone, and the cross-section cutting through the contact between the shale-free deposit (mainly sandstone ore) and the deposit located in sandstone, shale and dolomite.

1 – top part of white sandstone cemented with dolomite, 2 – typical mineralised white sandstone, 3 – massive chalcocite ore, 4 – relicts of the laminated ore, 5 – anhydrite-cemented sandstone).

B12.2 Field stop B2: Weissliegend sandstone, paleodunes and massive copper ores – Rudna mine

An intense copper sulphide mineralization occurs in the Weissliegend sandstone as spots, nests, cementations and streaks. This mineralization overlaps the earlier phase of the disseminated character. Different stages of replacement can be observed, including clay cement by carbonates and secondary silica, clay-carbonate cement by sulphides and quartz grains by sulphides. Locally, in the uppermost parts of the sandstone underlying the copper-bearing shales, a formation of pure chalcocite cement and also chalcocite masses with only relics of corroded detrital grains led to the massive cementational copper sulphide ores (Fig. B20). This type of ore is especially common in the areas of the sandstones elevations (paleodunes) in the Rudna Mine, although in that case massive sulphide bands often occur directly under the dolomite covering (the shale is missing). In the mining area the WL roof is very uneven and shows various relic paleomorphological features. Five white sandstone elevations have been distinguished, the majority of them situated in the Rudna Mine area (Mayer & Piestrzyński, 1985; Błaszczyk, 1981; Wodzicki & Piestrzyński, 1994). They are characterized by a lack of copper-bearing shale, direct contact with the highly differentiated overlying carbonate rocks, and greater thickness of both the WL deposits (up to 43 m) and the ore zone. Their slopes dip locally up to 25° whereas the regional dip is 2–5°. The thickness of the ore zone may reach 26 m. Some of the elevations contain large anhydritic zones, extending from anhydrite-rich Werra carbonates to the WL in an irregular fashion and where ore is peripheral. It has been suggested that the anhydrite event post-dates the peneconcordant ore mineralization. It is also possible that local anhydrite bodies in the Weissliegendes could result from evaporation of seawater and the resulting salt pans formed periodically on the surface of the elevations.

Studies of sulphur isotopic and chemical composition of several types of copper sulphide mineralization in one such elevation (Southern Elevation of Rudna, Sawlowicz & Kosacz, 1995) (Fig. B21), which lacks copper-bearing shale cover and anhydrite bodies, suggest differentiated processes of sulphides supply (closing of the BSR system, the release of sulphur from organo-sulphur complexes during diagenesis and possible supply of additional sulphur both from the Werra anhydrite and the Rotliegend sulphates). The copper reservoir appears to be generally homogeous. The origin of the massive copper ores in the elevations of

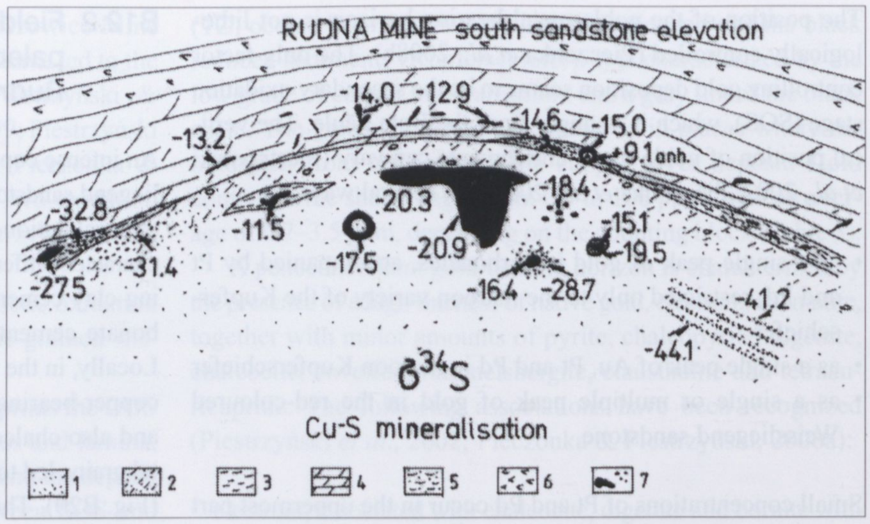


Fig. B21. Schematic distribution of ore structures of Cu-S minerals and their sulphur isotopic composition in the Southern Elevation of Rudna (after Sawlowicz & Kosacz, 1995)

1 – sandstones, 2 – dolomitic sandstone, 3 – shale, 4 – dolomite, 5 – sandy shale, 6 – anhydrite, 7 – ore; not to scale;

Weissliegend may be explained by the interaction of copper-bearing solutions from the underlying Rotliegend and hydrogen sulphide accumulated in the elevation structural trap, which probably originated mainly from the surrounding Kupferschiefer shale.

Where anhydrite bodies are present copper sulphides may be displaced by the anhydrite and shifted downward from the elevation. Elevations are not covered with the Kupferschiefer band, and covering dolomite is characterized by high porosity. These factors as well as typical structures of ore displacement (Figs. B9, B10) suggest invasion of oxidized barren sulphate-rich brines from the Zechstein evaporates.

B12.3 Field stop B3: Copper sulphide rhythmites in the Weissliegend sandstone – Rudna Mine

Spectacular sets of rhythmic copper sulphide bands occur in the sandstones, exclusively beneath the Kupferschiefer, and are to be found in all mines of the Lubin-Głogów district (Mayer & Piestrzynski, 1990; Sawlowicz & Wedepohl, 1992) (Fig. B22).

Characteristics:

- from two to sixty layers composed of copper sulphides, rarer Cu-Fe sulphides
- position 0.5 to 1.5 m below the Kupferschiefer
- thickness of a layer = ~1 cm,
- distance between layers = ~2-3 cm
- typically sharp lower boundary
- sulphur isotopes – getting heavier in laminae downwards in the set (–44 to –38‰).

The most probable origin is that bands formed diagenetically by diffusion, similar to the Liesegang rings, through the Ostwald-Prager reaction (Sawlowicz & Wedepohl, 1992) (Fig. B23). Sulphur diffused from the overlying shale whereas copper ions were present in or migrated into the upper part of the Weissliegend sandstones from below. Sulphur isotopic composition of copper sulphides suggests their probably very early deposition.

Fig. B22. A typical set of rhythmic Cu-S bands in the Weissliegend sandstone (Rudna Mine).

Acknowledgements

The help of authorities and mining geologists from KGHM Polska Miedz in preparation of the field guide and the underground visits is gratefully acknowledged. Volker Hoeck is thanked for a review.

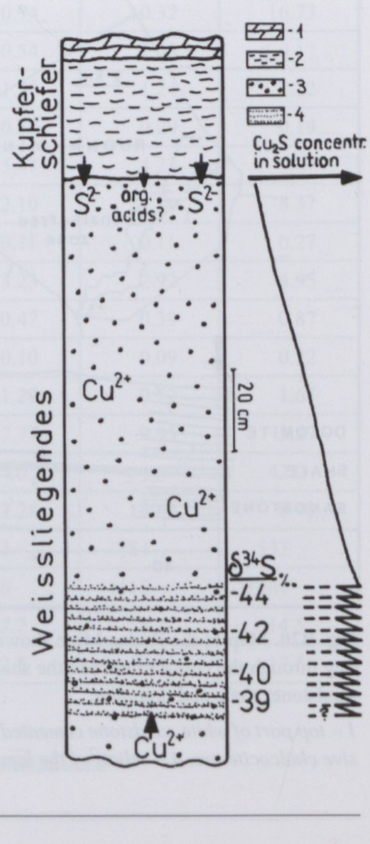


Fig. B23. Idealized model of the formation of rhythmic sulphide bands in the Weissliegend (after Sawlowicz & Wedepohl, 1992)

1 – dolomite, 2 – Kupferschiefer shale, 3 – Weissliegend sandstone, 4 – copper sulphide bands).

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Appendix – Itinerary for IMA 2010 PL3 Field trip

Saturday, August 28, 2010 (Day 1)

09.00–	Travel from Budapest to Wałbrzych, ~600 km, 10h

Sunday, August 29, 2010 (Day 2)

07.30–08.00	Breakfast
08.00–09.00	Travel from hotel to Field stop A1.
09.00–10.30	Field stop A1 – Wałbrzych-Podgórze (N50°44'27.6" E16°18'18.99").
10.30–11.30	Travel to field stop A2.
11.30–13.00	Field stop A2 – Czadrówek (N50°46'16.45" E16°2'53.75").
13.00–14.30	Travel to field stop A3.
14.30–16.00	Field stop A3 – Organy Wielisławskie (N51°2'4.13" E15°52'9.51"). Lunch in the field.
16.00–16.30	Travel to Field stop A4.
16.30–18.00	Field stop A4 – "Piekiełko" valley (N51°3'5.6" E15°51'40.4").
18.00–19.30	Travel to hotel at Lubin. Accommodation, dinner.

Monday, August 30, 2010 (Day 3)

06.30–07.00	Breakfast
07.00–07.30	Travel from hotel to the Polkowice Mine (Mine stop B1)
08.00–13.00	Visit to the underground mine
13.00–13.30	Lunch
13.30–15.30	Visit to the processing plant and tailings dam
15.30	Return to the hotel
18.00	Dinner

Tuesday, August 31, 2010 (Day 4)

06.30–07.00	Breakfast
07.00–07.30	Travel from hotel to the Rudna Mine (Mine stops B2–B3).
08.00–13.00	Visit to the underground mine
13.00–14.00	Lunch
14.00–16.00	Travel to Wroclaw
16.00 –	Travel from Wroclaw to Budapest